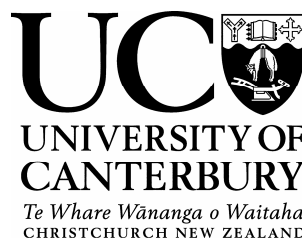


Groundwater flow patterns and origin on the North Bank of the Wairau River, Marlborough, New Zealand.

A thesis submitted in partial fulfilment
of the requirements for the Degree
of
Master of Science in Engineering Geology
in the
University of Canterbury
by
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Frontispiece: The Wairau River and North Bank (Photo: T Dennis)

"We never know the worth of water till the well is dry."

~Thomas Fuller, 1732

ABSTRACT

The North Bank area lies on the north side of the Wairau River, Marlborough, New Zealand, bounded by the Richmond Ranges to the north and the Wairau River to the south. The North Bank is an interactive zone where groundwaters and surface waters from North Bank tributary valleys mix with waters of the Wairau River. This investigation aimed to define the nature and origin of groundwaters of the North Bank area.

Stable isotopes of oxygen and hydrogen, along with hydrogeochemistry, were utilised in order to define the spatial extent of the North Bank riparian margin and delineate the Wairau River-groundwater interface. Distinct stable isotopic signatures differentiate ground and surface waters that come from high mountain catchments versus those that arrive more locally at lower altitude. The results gathered by this study demonstrated stable isotopes to be the most powerful forensic tool capable of distinguishing Wairau River water from North Bank tributary groundwater sources. In contrast, hydrogeochemical characteristics of the waters of the North Bank were young and chemically dilute in nature, which made them chemically indistinguishable from waters of the Wairau River.

Geomorphological mapping was conducted in order to investigate the relationship between groundwater flow patterns and geomorphology upon the North Bank. Geomorphology, in the form of prominent fluvial terraces, was found to play a role in limiting the extent of Wairau River influence to groundwater to either low-lying Q2 Speargrass Formation, Q1 Rapaura Formation alluvium or the Wairau River channel itself.

Aquifer pump testing and water level observation carried out in the Waikakaho Valley revealed a plentiful groundwater resource in the local context. Like other tributary valleys within the North Bank study area, surface water and groundwater were found to be chemically and isotopically linked to one another which points to an interconnected ground and surface water resource, larger than first thought. Driven by recharge by the Waikakaho River, the groundwater resource has development potential, and continued monitoring will further define the hydrogeological system and ensure long term sustainable use.

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Chapter 1

INTRODUCTION AND OBJECTIVES

1.1 PROJECT BACKGROUND

The North Bank area lies on the north side of the Wairau River, Marlborough, New Zealand, bounded by the Richmond Ranges to the north and the Wairau River to the south. The North Bank extends alongside the Wairau River approximately 50 kilometres from Top Valley in the west to Cloudy Bay in the east. North Bank tributary valleys drain the Richmond Ranges and contribute to springs, streams and aquifer through-flow within the tributary valleys, and ultimately contribute water to the Wairau River. The North Bank is therefore an interactive zone where ground- and surface-waters from the north mix with waters of the Wairau River. The exact nature and origin of groundwaters of the North Bank have yet to be constrained along its entire extent.

The wider Wairau valley and plains have been the focus of much hydrogeological research due to a high annual potential evapotranspiration deficit and a high water demand. The Wairau River – groundwater interface on the South Bank is known to shift seasonally, with spring and summer representing the maximum and minimum influence of the Wairau River respectively. While this seasonal change is also likely on the North Bank, the temporal and spatial extent of the Wairau River – groundwater interface on the North Bank is poorly understood. This project aims to review the recharge processes within the North Bank tributary riparian margin, through the collation of existing historical data together with the collection and interpretation of new data, to add to the current scientific understanding of the origin, nature and flow direction of groundwater on the North Bank of the Wairau Valley.

1.2 STUDY OBJECTIVES

The overall objective of this study is to review the recharge processes within the North Bank tributary riparian margin, and to synthesise currently available information. Specific objectives are to:

- Define the spatial extent of the North Bank riparian margin, and quantify residence time and through-flow in North Bank riparian aquifers.
- Determine seasonal aqueous geochemistry for the North Bank tributary riparian margin and examine how mineralogy influences, or correlates with, aqueous geochemical constituents.
- Develop a conceptual hydrogeological model for the North Bank riparian margin and tributary valleys.

1.3 STUDY AREA

The study area is approximately 80 square kilometres and encompasses the North Bank riparian margin alongside the Wairau River, including major northern tributary valleys that extend into the Richmond Ranges (Figure 1.1). Tributaries include: Top Valley, Timms Creek, Cat Creek, Pine Valley, Bartletts Creek and the Onamalutu River, west to east respectively. The tributary valleys have been grouped into three sub-areas for more detailed assessment. These are the eastern-most valley of Waikakaho, the middle-pairing of Kaituna and Onamalutu and the western-most grouping of Cat Creek, Timms Creek and Top Valley. The eastern-most Waikakaho valley and the western-most grouping of Cat Creek, Timms Creek and Top Valley will be detailed case study areas. The middle-pairing of Kaituna and Onamalutu, where Marlborough District Council has collected stable isotope data, will be reviewed and synthesised. Other areas that fall outside of the immediate North Bank study area, such as Pukaka Drain, will also be examined in order to complete the stable isotope picture along the North Bank.



Location of Study Area

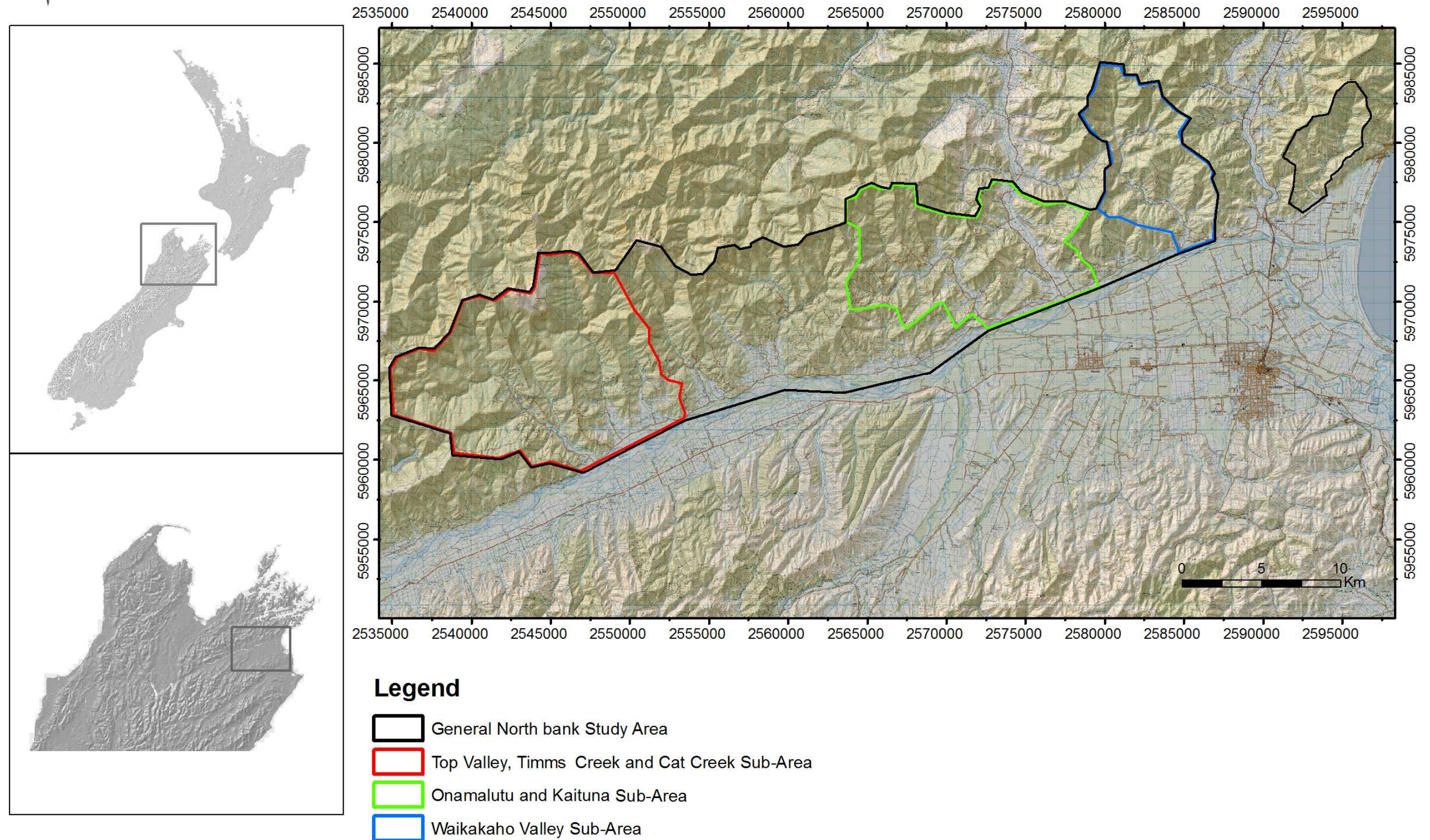


Figure 1.1 Location of the North Bank study area (Inset: Maps indicate the location of the study area within the South Island of New Zealand).

1.4 CLIMATE

The Wairau Valley has a mild dry climate characterised by high sunshine hours and a high annual potential evapotranspiration deficit (2477 hours in 2009 and around 600 millimetres per annum respectively - NIWA, 2010). Warm, dry and settled weather predominates during summer while winter days are usually mild with frosty, cold nights. The mean summer temperature is 17.6 °C, while mean winter temperature is 8 °C, both at Blenheim Airport at Woodbourne in the central part of the valley (NIWA, 2010). Climate data collected at Blenheim Airport from 1971 to 2000 can be seen in Table 1.1 and is fairly representative of the Wairau Valley at large.

Table 1.1: Mean annual climate values. Data are mean annual values for the 1971-2000 period, with at least 5 complete years of data (data source: NIWA, 2010).

	Rainfall	Wet-days	Sunshine	Temperature	Ground frost	Wind	Gale days
				Mean		mean speed	mean speed at least
Location	mm	≥ 1.0 mm	hours	°C	days	km/h	63km/h
BLENHEIM	655	76	2409	12.9	60	13	4

The discrepancy between mean monthly rainfall and mean monthly potential evapotranspiration can be seen in Figure 1.2 with mean monthly potential evapotranspiration typically and significantly greater than mean monthly rainfall.

While a high annual potential evapotranspiration deficit exists for the majority of the Wairau Valley, rainfall is much higher for the North Bank of the Wairau River compared to the South Bank. A rainfall isohyet map is a map with lines joining points that receive equal precipitation, as shown in Figure 3. Figure 3 depicts the elevated amount of rainfall the more humid North Bank study area receives in comparison to the sub-humid to semi-arid Wairau Valley floor. This can be attributed to heavy orographic rain generated by north-westerly weather systems impacting on the Richmond Range resulting in heavy rainfall on the North-Bank. The Richmond Range offers little protection from moist north-westerly airstreams associated with the passage of cold fronts, and it is from this direction that most precipitation is received (Rae, 1988).

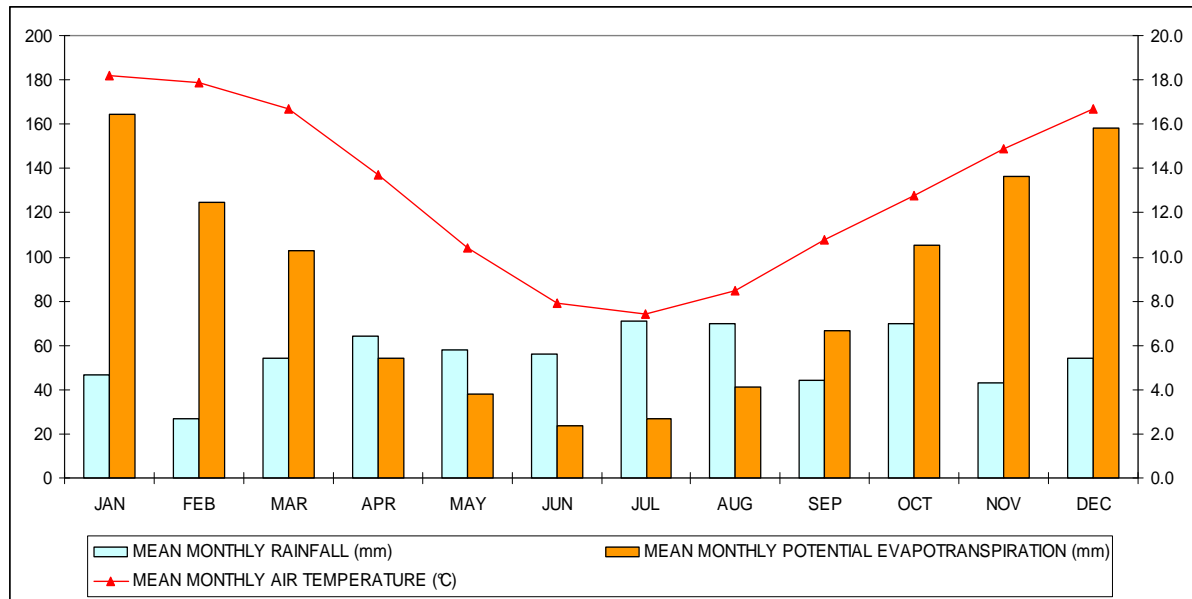


Figure 1.2: Comparison of mean monthly potential evapotranspiration and rainfall at Blenheim Aero AWS station, along with mean monthly air temperature. The data covers the period 1992 to 2010 (data source: NIWA, 2010).

In contrast, the South-Bank, which includes the majority of the Wairau Valley, experiences a rain shadow effect caused by the Southern Alps mountain range, blocking the prevailing westerly weather systems. Rainfall from westerly flows are generally confined to high country areas and such airflows are generally dry and often very warm, bringing with them föhn winds. North-easterly conditions bring only minimal rain to the Wairau Valley, while heavier rainfalls occur in the Marlborough Sounds. Easterly airstreams tend to affect only coastal regions, and much of the Wairau Catchment remains unaffected. Southerly conditions again generally affect only coastal regions, however, can result in easterly airflows with the southerly being channelled into the Wairau Valley (Rae, 1988).

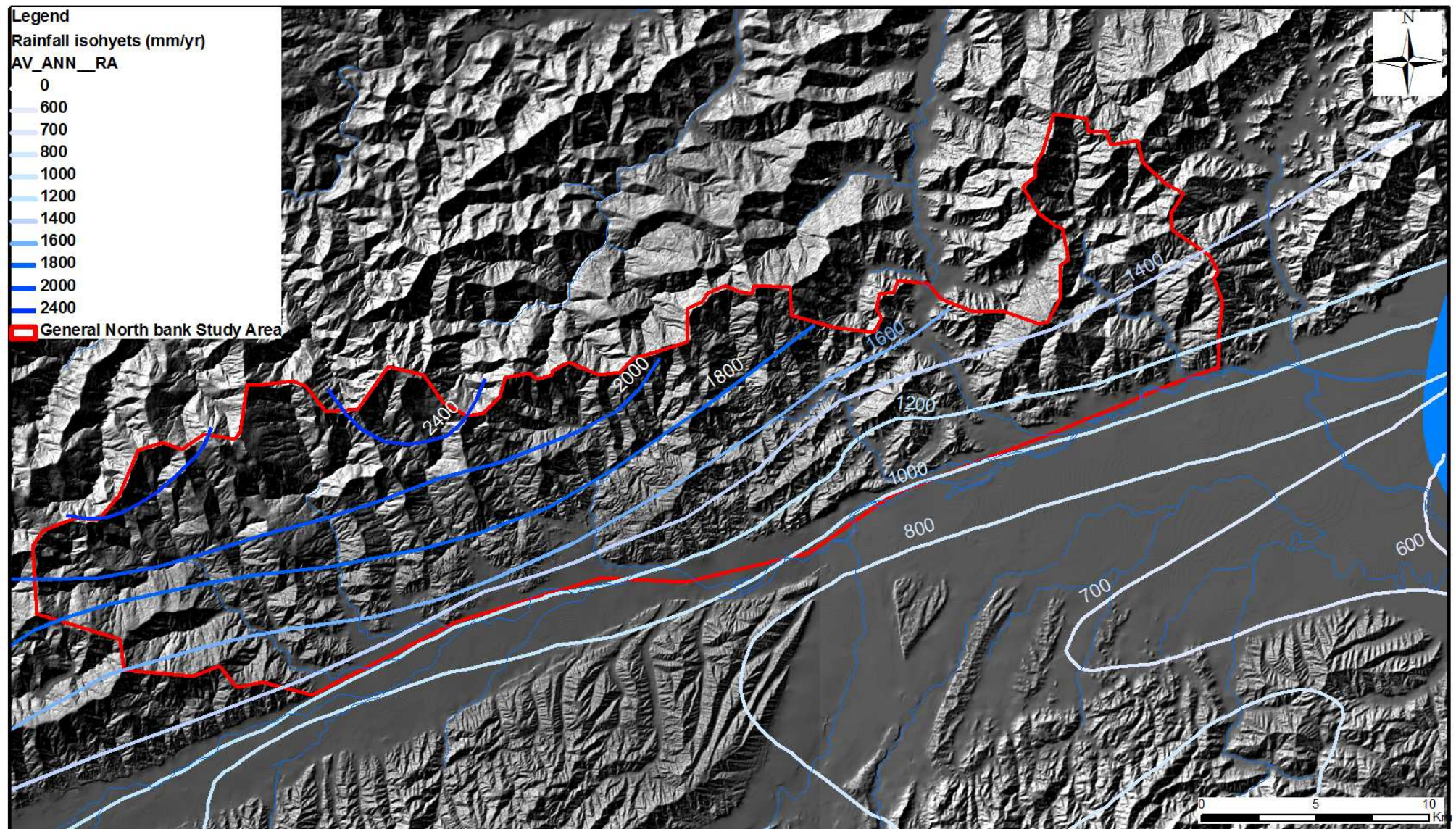


Figure 1.3: Rainfall isohyet map (Data source: Rae, 1988).

1.5 SOILS

The soils of the North Bank area are formed mainly from high grade metamorphic rocks (schist), weakly metamorphosed schistose greywacke, and from small areas of alluvium on the valley floor (Rae and Tozer, 1990). As most of the North Bank area consists of chlorite-rich schist, the soils which develop on this schist are low in fertility (Rae, 1988). The soils are described as yellow-brown earths by the Soil Bureau (1968) and have been grouped climatically by Rae and Tozer (1990), with those that experience a weak dry season and those that experience a negligible dry season. Rae and Tozer's (1990) description of the soils have been tabulated and are shown in Table 1.2.

Table 1.2: Description of North Bank soils, after Rae and Tozer (1990)

	Weak dry season			Negligible dry season	
Altitude	Below 450m			Above 450m	
Mean annual rainfall (mm)	1000 - 1500mm			1500 - \geq 2000m	
	Kaituna & Koromiko Soils	Tuamarina hill soils	Onamalutu steepeland soils (part)	Onamalutu steepeland soils (part)	Patriarch steepeland soils
Slope (degrees)	0-15	16-25	16-25, >25	16-25, >25	>25
Drainage class	Well-drained	Moderately well-drained	Well-drained	Well-drained	Moderately well-drained
Fertility	Few limitations for agricultural and horticultural use	Limitations for pastoral and forestry use of nutrient deficiencies and slope	Limitations for pastoral and forestry use of nutrient deficiencies and slope	Limitations for pastoral and forestry use of nutrient deficiencies and slope	Major limitations for pastoral and forestry uses of severe erosion, slope and short growing season

Description	Greyish silt loam topsoils overlying firm to friable yellowish brown silt loam subsoils often containing stones	Greyish silt loam topsoils overlying firm, pale yellow silty clay loam subsoils with common grey mottles	Greyish brown topsoils overlying firm yellowish brown stony silty clay loam subsoils	Greyish brown topsoils overlying firm yellowish brown stony silty clay loam subsoils	Thin, dark brown heavy silt loam topsoils overlying friable to very friable yellowish brown heavy silt loam subsoils
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The majority of soils found on the North Bank belong to the Onamalutu series while soils found in the tributary valley floors are mostly comprised of Kaituna or Tuamarina series (Figure 1.4).

In addition to the soils described by Rae and Tozer (1990) as having a weak dry season or a negligible dry season, Waimakariri and Kaiapoi soils are also present in the study area close to modern floodplains. Waimakariri soils are well-drained soils formed from recent loamy alluvium. Typical profiles have greyish brown topsoils overlying olive sandy loam or silt loam substrates (Rae and Tozer, 1990). Kaiapoi soils are moderately well drained and imperfectly drained deep loamy soils formed in recent alluvium. Representative profiles have very dark greyish brown silt loam topsoils overlying grey and ochreous mottled heavy silt loam subsoils (Rae and Tozer, 1990).

Soils of the North Bank are all relatively well-drained and show a distinct trend in leaching and podsolisation in relation to increasing rainfall and cooler temperatures with increasing altitude (Rae and Tozer, 1990). Steep slopes with podsoils limit current landuse practices to forestry, while utilisation of more fertile soils in tributary valleys is represented by more varied agriculture, where slopes are gentle.

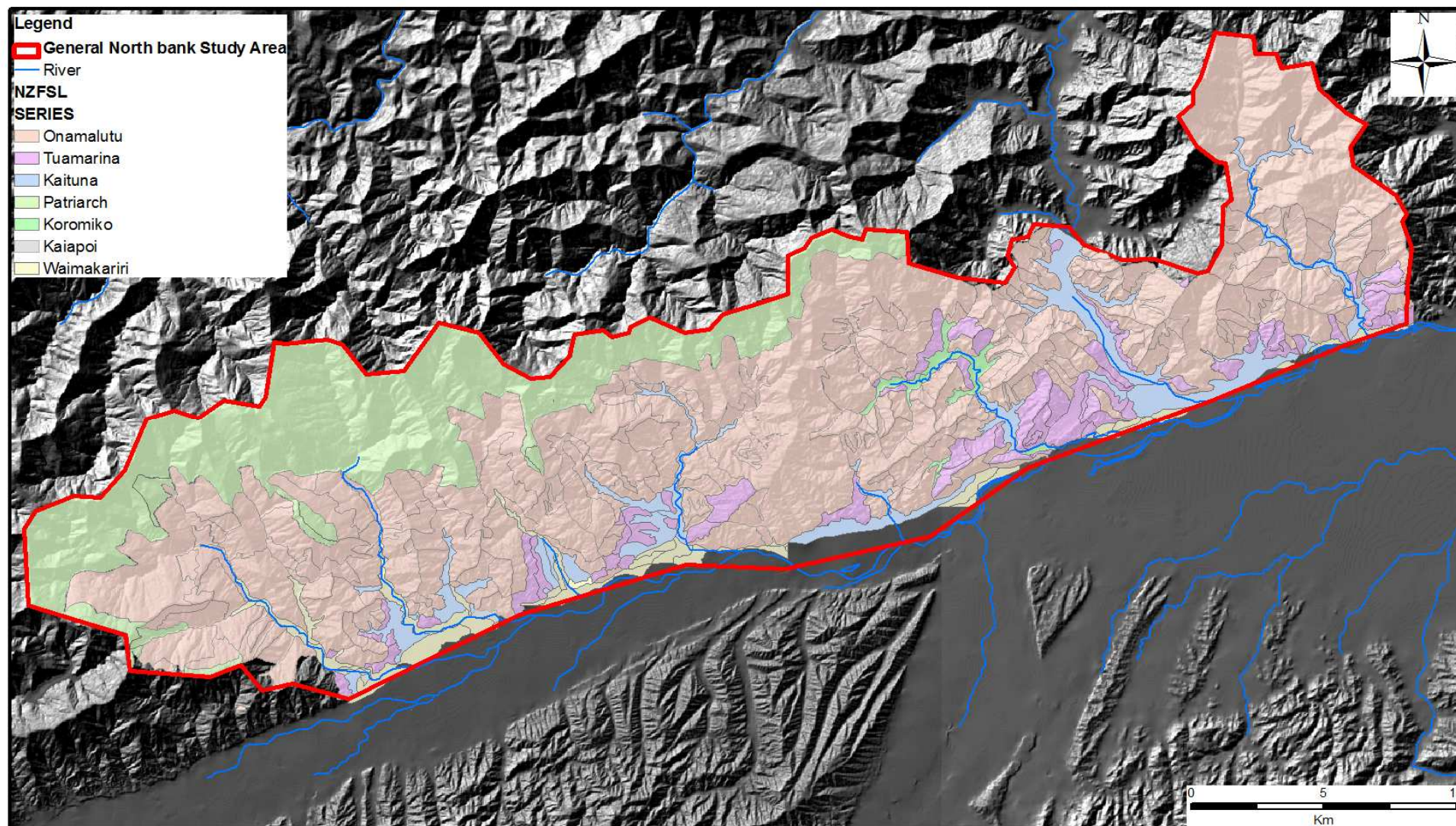


Figure 1.4: Soils map of the North Bank (Data Source: New Zealand Fundamental Soils Layer, 2000)

1.6 VEGETATION AND LANDUSE

Historically, the North Bank area has been under the cover of various beech forest and was largely untouched by fires lit by Maori who inhabited the area prior to European occupation. In the 19th Century, vegetation clearance for farming occurred in the North Bank tributaries where the valleys open, close to their junction with the Wairau. Many of the steep slopes not within Mt Richmond Forest Park (where the predominant vegetative cover is still beech forest) are planted in *Pinus Radiata* forest. Current landuse practices are still largely forestry on steep slopes, while more varied agriculture such as sheep and dairy farming occur where slopes are gentle. A recent shift to viticulture has also been observed with the establishment of vineyards on flat low-lying historic floodplains.

1.7 PREVIOUS WORK

While the geology and water resources of the wider Wairau Valley have been extensively studied, research of the North Bank riparian margin itself has been sporadic and often as an addendum to the wider Wairau Valley. A review of the present knowledge of the wider Wairau Valley is therefore useful in order to frame the context in which this project sits. Previous work can be broadly categorised into the following fields of geology and hydrogeology.

1.7.1 Geology

The geology of the Wairau Valley has been well documented by Brown (1981) who studied the late Quaternary geology and drew upon the previous work of Suggate (1965), and Lensen (1976). Suggate paid particular interest to the late Pleistocene geology in the upper Wairau Valley describing the glacial outwash deposits also present in the study area, while Lensen mapped the Wairau Fault to assess past tectonic activity. Brown synthesised their work, along with geological mapping of his own, to produce a 1:250,000 scale map that outlines the geology of the Wairau Valley and Plain.

More recently, Rattenbury, et al. (1998) and Begg and Johnston (2000) produced 1:250,000 scale maps of the Nelson and Wellington areas respectively, as part of Geological & Nuclear Sciences QMAP programme. As the study area straddles these two QMAP sheets, both geological maps provide a useful base on which to further refine geologic detail for the North Bank. Johnston's (1994) 1:50,000 scale map, entitled 'Geology of the Richmond Range', provides a good amount of detail for the western-most parts of the study area, specifically Top Valley and Timms Creek, and will also be utilised in map construction.

1.7.2 Hydrogeology

The hydrogeology of the Wairau Valley and Plains has been investigated in the past in order to determine groundwater occurrence and aquifer characteristics. Investigations that have focused on the groundwater occurrence and aquifer characteristics within the Wairau Valley and Plains include Brown (1972), Rae (1988), Cunliffe (1988), McCarthy (2008), MDC (2007) and various well tests performed by well drillers to ascertain well performance. Groundwater within the Wairau Valley has been found to exist within a number of significant aquifers, namely the Wairau Aquifer, the Southern Valleys Aquifers and the Deep Wairau Aquifer.

Additionally, there have been studies using environmental hydrochemistry and isotope hydrology techniques to determine groundwater flow direction, nature and origin. The relationship between surface waters of the Wairau River and groundwater in its riparian margins have been examined using hydrogeochemical and isotopic approaches by several authors (Taylor et al., 1992, Taylor, 2004, Stewart, 2006, Stewart, 2008). Their findings have indicated that surface water and groundwater of the Wairau Plain, Wairau Valley and Wairau River are an interconnected resource with isotopic tracers such as oxygen-18 and tritium proving to be a powerful tool in constraining the age and source of groundwater. Delta oxygen-18 ($\delta^{18}\text{O}$) values for Wairau River water are relatively negative due to the high altitude of the Wairau River catchment, while $\delta^{18}\text{O}$ values for precipitation upon the plain and within tributary valleys are significantly less negative – both compared to Vienna Standard Mean Ocean Water (V-SMOW). These characteristics allowed interpretation of the relative contribution to groundwater recharge both the Wairau River and surface infiltration make respectively. Taylor (2004) found little evidence for Wairau River-recharge of groundwater in the Kaituna tributary area from stable isotope analysis; yet the possibility exists for Wairau

River-recharge to groundwater to be occurring elsewhere along the North Bank of the Wairau River. Further examination of the interaction between The Wairau River and its North Bank tributary valleys and the Wairau River – groundwater interface on the North Bank using stable isotope and chemical analysis will be beneficial and build upon the work previously carried out.

1.8 RESEARCH METHODS

Initially a desktop review of background information was begun with staff from the Marlborough District Council who were extremely helpful in supplying reports and historic documents relevant to the study. Past geological exploration, specifically historic gold-exploration bore logs made available were examined, constructing geological cross-sections of the northern tributary valleys where data exists.

Fieldwork began in May 2009 with the drilling of two observation wells in the Waikakaho Valley (4-6 May and 13 May). The purpose of the two wells, adjacent to the Waikakaho River and some 10 metres apart, was to allow a geological description of the strata infilling the valley to be gathered during drilling, as well as to enable an aquifer pump test to be performed at a later date. A temporary water level recorder was also lowered into the observation well to allow fluctuations in groundwater levels to be recorded.

Field reconnaissance began from 22 June in order to find suitable wells, along with springs and streams, to sample ground- and surface- water respectively. This served the dual-purpose of finding potential sample sites for an extensive hydrogeochemical and stable isotope sampling survey, as well as adding information to the Marlborough District Council's well database. This was a useful exercise, as when meeting with the various landowners potential problems and ideas for sampling were raised, and photographs of wells along with GPS coordinates were taken.

Ground- and surface water sampling was carried out 3-6 August. Thirty-five sites were visited over the course of 4 days in order to collect water samples for chemical and oxygen isotope analysis. A standard sample collection procedure was followed as per a hydrogeochemical tracer project and will be discussed in more detail in Chapter 4. Thirty-three sites had a

comprehensive suite of chemical analyses performed by Cawthron Laboratories, Nelson. In addition, each of the sample sites had their oxygen isotope ratios tested by Dr Travis Horton at the University of Canterbury's Stable Isotope Laboratory. Two more sites (Are Are Creek and Pukaka Drain) were included to broaden the study area, and had their respective oxygen-isotope ratios tested.

Late September saw the commencement of field mapping in order to complete the geomorphological picture of the field area. The geomorphology of the field area was thought to likely play an important role in the nature and occurrence of groundwater in the North Bank riparian margin. Mapping was carried out at a suitably detailed scale of 1:10,000 and aimed to link the geology and the hydrogeology of the area together. The end-product is to be a 1:10,000 digital geomorphic and geologic map at the junction of each of the northern tributary valleys with the Wairau River.

1.9 PROJECT FORMAT

This thesis is divided into 8 chapters. Chapter 2 outlines the geology and geomorphology of the area, incorporating both past geological investigation and field mapping that the author carried out (ultimately presented in Chapter 5, Chapter 6 and Chapter 7 in relation to stable isotope results). Chapter 3 discusses the surface hydrology, and hydrogeology. Chapter 4 details the groundwater chemistry of the North Bank and presents the results of a chemical and isotope sampling survey. The use of Stable Isotopes in the North Bank area are discussed and presented in Chapter 5. Chapter 6 is a detailed case study of the Waikakaho Valley where groundwater occurrence, residence time and quantification of through-flow has been sought. Chapter 7 examines Top Valley to Cat Creek as another case study and will detail groundwater flow directions and origin. Chapter 8 summarises all the data and interpretations made in preceding chapters and makes recommendations for future investigation.

Chapter 2

GEOLOGY AND GEOMORPHOLOGY

2.1 INTRODUCTION

The geology of the study area on the North Bank is based on mapping from various sources and primarily from the QMap of the Wellington and Nelson and areas completed by Rattenbury, et al. (1998) and Begg and Johnston (2000) respectively. The geology of the Wairau region is described to place the geological setting in context. The stratigraphy of the study area within the North Bank study area is summarised, with emphasis on the glacial outwash formations and alluvial deposits which form the lithological constraints on the presence of groundwater.

2.2 REGIONAL SETTING

Structural Setting

New Zealand is located on the plate boundary between the Pacific and Australian plates (Figure 2.1 inset). The transition between oblique convergence and subduction of the Pacific plate beneath the Australian plate in the Hikurangi subduction zone in the north, and the dextral reverse oblique slip due to oblique collision along the Alpine Fault in the south is accomplished by the Marlborough Fault System (MFS). The MFS is a series of predominantly right lateral strike-slip faults in the northern South Island of New Zealand with the most prominent being (from northwest to southeast) the Wairau, Awatere, Clarence, Kekerengu, and Hope Faults (Zachariassen et al., 2006 - Figure 2.1). The approximately 100 km long active Wairau Fault is the north-eastern continuation of the Alpine Fault and runs from the northern end of the “The Bends” area of the Alpine Fault (Suggate, 1979) near Lake Rotoiti to Cloudy Bay in the east, where it possibly travels some distance offshore. The fault is a single strand from Lake Rotoiti to Wairau Valley township where it bifurcates and continues as two strands to Renwick, approximately 15 km from the coast (Figure 2.2, attached Geological Map, back pocket). Current motion on the Wairau Fault is approximately 4 mm per annum (Begg & Johnston, 2000).

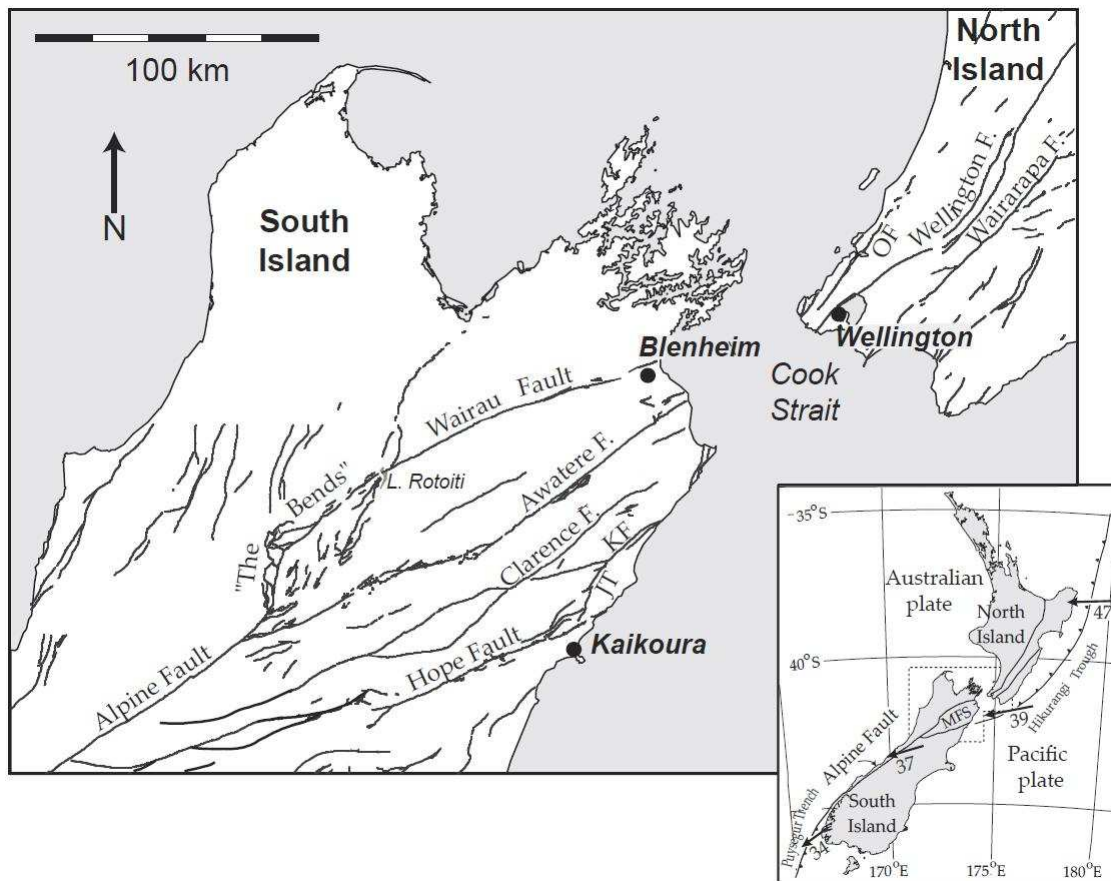


Figure 2.1: Structural setting of the Marlborough Fault System (Zachariassen *et al.*, 2006)

The Wairau fault separates the two major north-east tilted blocks of rock that make up the Wairau Catchment. These are the Marlborough Sounds block to the north of the fault, and the Awatere block to the south (Brown, 1981). The Marlborough Sounds block, upon which the study area sits, consists of rock basement of the Caples Terrane and Rakaia sub-terrane, while the Awatere block rock basement consists of Pahau sub-terrane (Figure 2.3). The contact between Caples and Rakaia terranes is a complex fault zone that is largely overprinted by metamorphism and penetrative deformation (Begg and Johnston, 2000). The Wairau Fault has been significant in defining the course of the Wairau River, which lies in the fault-angle depression towards the north side of the valley floor.

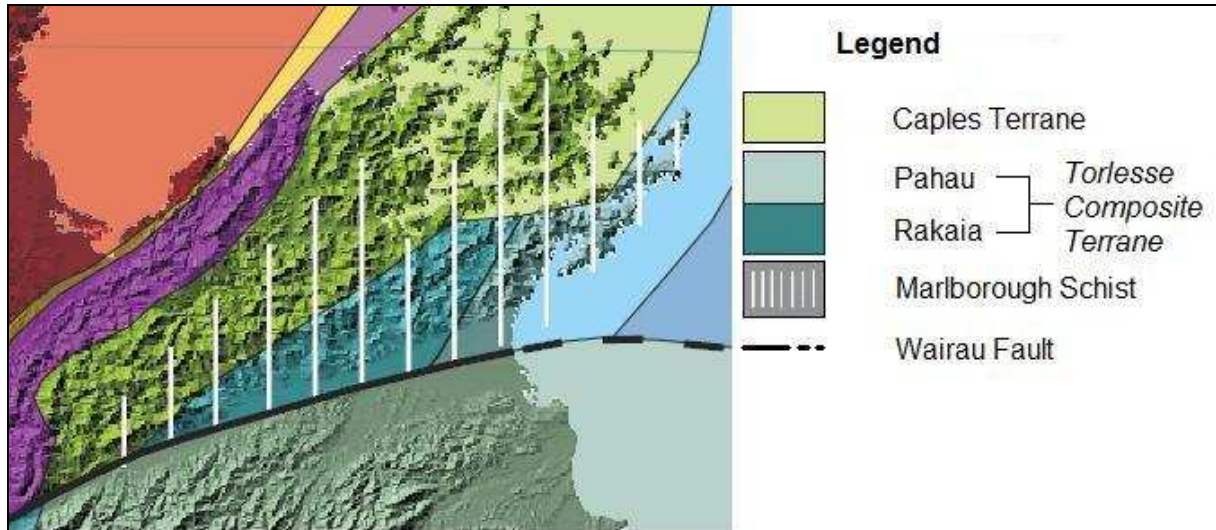


Figure 2.3: Geological Terrane Map of Marlborough. The regional tectonic metamorphic overprinting resulting in the formation of Marlborough Schist is equivalent to that of the Haast Schist (Data Source: GNS, 2001)

2.3 STRATIGRAPHY

A 1:250,000 scale geological map for the study area is contained in Figure 2.2 (back pocket). The geology outside of the immediate North Bank study area is also shown on Figure 2.2 to place the diverse geological setting in context. North Bank geology is detailed further (in relation to ground- and surface-water oxygen isotope values) in 1:10,000 scale maps presented in Chapters 5, 6 and 7, as referred to in text.

2.3.1 Basement Rocks

Rock basement and alluvial derivatives in the study area are composed of Pelorus Group of the Caples Terrane and Rakaia subterrane, both superimposed by a zone of regional tectonic metamorphic overprinting. This overprinting, locally referred to as the Marlborough Schist Zone and correlated with the Haast Schist of Otago, has resulted in metamorphosed greywacke and argillite that forms the majority of the North Bank (Rae, 1988).

The Marlborough Schist is laminated and segregated schist, commonly with well-developed lineations that fall into Bishop's (1972) textural zones IIIA-IV. These zones are characterised by strong foliation and display incipient to well-developed mineral segregation (Figure 2.4). The schists are dominantly grey and pelitic and are inferred to have been metamorphosed grey quartzo-feldspathic sandstone-mudstone sequences with sparse, poorly bedded, thick

sandstone horizons. The mineral assemblage quartz-albite-muscovite-chlorite dominates the schists, which correspondingly signifies they belong to the chlorite zone of the greenschist facies. Locally, biotite is present, indicating transition into the biotite zone of the greenschist facies (Mortimer & Little, 1998). Formation of the Marlborough Schist in the suture zone of the Caples Terrane and Pahau Sub-terrane occurred during the Early or Middle Jurassic (Begg and Johnston, 2000).

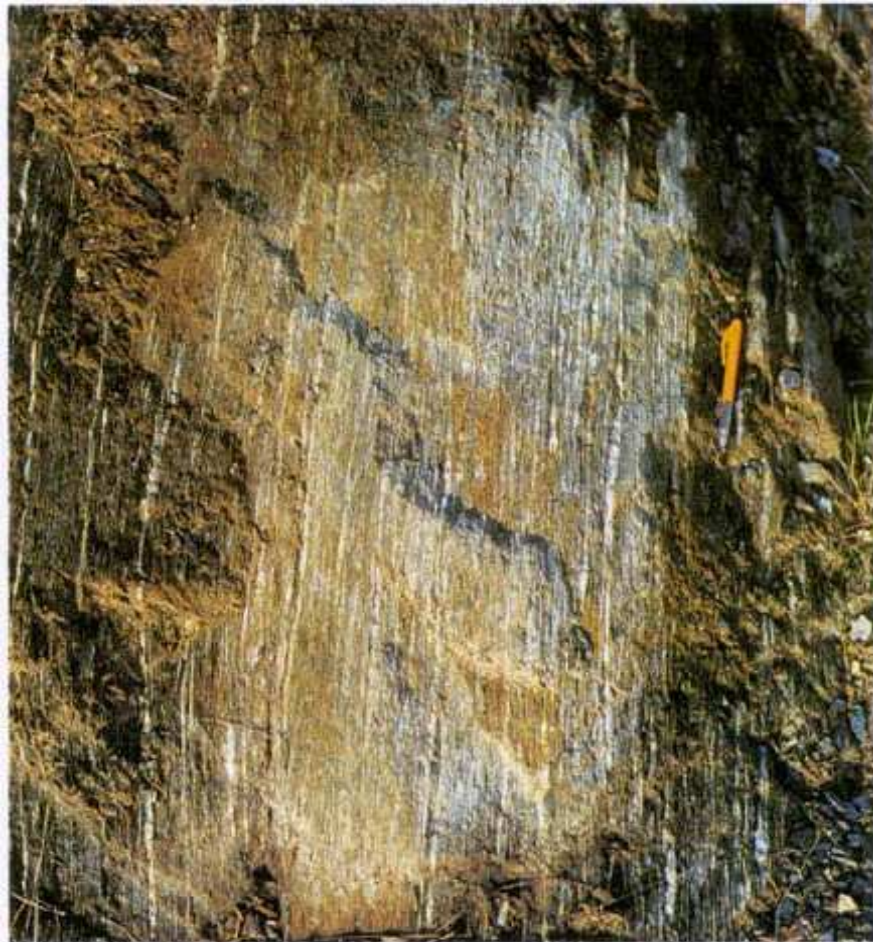


Figure 2.4: Segregated textural zone IIIB Marlborough Schist derived from metamorphosed Triassic-Jurassic Rakaia subterrane of the Torlesse Supergroup, North Bank, Wairau River (Begg and Johnston, 2000)

Interesting to note are local instances of iron- and manganese-rich metachert found within schist, outcropping in the Onamalutu Valley. Although limited in extent, the metachert contains up to 7 percent manganese, mainly as piemontite and spessartine-rich garnet, and is located south side of river near Onamalutu Domain (Watters and Challis, 1985).

The strongly metamorphosed schist is more diverse in terms of mineral deposits than the weakly metamorphosed sedimentary greywacke and argillite that make up rock basement to the south of the Wairau River (Rae, 1989). However, due to both the high rainfall and severe weathering the North Bank has undergone, in addition to being formed under conditions of higher temperature and pressure, the North Bank basement has a lower tendency to release minerals than south bank lithologies. This is reflected in lower overall stream conductivities for tributaries draining the North Bank versus the South Bank (Cunliffe, 1988)

2.3.2 Quaternary Deposits

The Manuka Formation is the oldest quaternary deposit, once present in the study area, corresponding to Oxygen Isotope Stage 10 and correlated with the Nemona Glaciation 370-320 ka (Suggate, 2004, 1988a and 1988b – Table 2.1). A series of notched spurs, at 120m and 90-100 m above the valley floor, extend down the Wairau Valley (most noticeably on the south side), and were probably cut immediately prior to deposition of aggradation gravel of the Manuka Formation. The gravel has subsequently been removed, although it is possible that isolated deeply weathered patches may remain in the study area (Johnston, 1994). The description of the aggradation gravel is made from deposits found at 60-200 metres elevation on the south side of the Wairau Valley where it is capped by 2-3 metres loess cover. The gravel consists of highly weathered, yellow and brown, poorly sorted sub-angular to sub-rounded gravel, sand and clay (Brown, 1981). The notched spur of MA₂ (90-100 m) located in lower Top Valley is too small to be shown in Figure 2.2 and instead shown in Figure 7.1 and Figure 7.12.

The Harry Formation corresponds to Oxygen Isotope Stage 8 and is correlated with the Waimaungan Glaciation 310k-238 ka (Suggate, 1988a – Table 2.1). This poorly exposed, weathered aggradation gravel has almost been entirely destroyed by erosion so that only a notched spur of greywacke remains (labelled HA in Figure 7.1 and Figure 7.12)

The Tophouse Formation corresponds to Oxygen Isotope Stage 6 (otherwise denoted as Q6) and correlates with the Waimea Glaciation ca. 186-ca. 128 ka (Begg & Johnston, 2000 – Table 2.1). Like the Manuka Formation, it is comprised of glacial outwash and fan material but differs from the Manuka Formation in displaying only a moderate degree of weathering, less surface dissection, and less loess cover, commonly capped by only up to 0.5 m (Suggate, 1965). It is thought to have filled the valley from the Tophouse area and subsequently eroded

away during interglacial periods (Brown, 1981). Isolated remnants of the Tophouse Formation occur in Top Valley with the aggradation surface about 40 m above the valley floor (Figure 7.1 and Figure 7.12 - Johnston, 1994). The gravel consists of weathered to slightly weathered brown and yellow, poorly sorted sub-angular to sub-rounded gravel, sand and silt.

The Roundell Formation corresponds to Oxygen Isotope Stage 4 (Q4) and is assigned to the early Otira Glaciation. A largely unweathered gravel, it forms a little-modified localised terrace remnant 30 metres above the valley floor (Figure 7.1 and Figure 7.12). The aggradation surface has a very thin cover of loess (Johnston, 1990).

The Speargrass Formation corresponds to Oxygen Isotope Stage 2 (Q2) and correlates with the Otira Glaciation 22.3 ka BP, culminating at ca. 18 ka BP (Suggate, 1990 – Table 2.1). The Speargrass formation is glacial outwash gravel from earlier glacial periods (Tophouse and Manuka Formations) and is the youngest and most extensive of the upper Quaternary gravels, forming an extensive aggradation surface ("Wairau surface" after Wellman, 1955) 15-20 m above the Wairau River, and at lesser heights in tributary valleys. Speargrass gravel is associated with poorly sorted fluvial deposits of gravel, sand, and clay. Clasts are relatively unweathered with a blue-grey colour (Brown, 1981). Permeability is lower than younger deposits reflecting a greater proportion of fines in the matrix, and when drilling, Speargrass gravels were found to be much tighter than the postglacial fluvial deposits (Brown, 1981).

The Speargrass Formation gravels can be distinguished from the Tophouse gravels by the lesser degree of weathering of clasts and their blue-grey colour. Except for extensive cutting of degradational terraces and local overtopping by fans, the surface is little modified, and capped by only a thin layer of loess. At 3-5 m below the "Wairau surface", minor terrace remnants are present which may possibly be another aggradation (rather than degradation) surface (Johnston, 1994).

Table 2.1: Glacial and interglacial stages of New Zealand and their corresponding formations within the Wairau Valley and North Bank study area. Modified from Suggate, 2004

***Manuka Formation previously assigned to Waimanga Glaciation by Suggate 1965, 1985.**

Stage	Formation	Duration (years BP)	Oxygen Isotope Stage
Aranuian Postglacial -fluvial	Rapaura		Q1
Otira Glacial	Speargrass	14,000 - 72,000	Q2–Q4
Kaihinu Interglacial		72,000 - 128,000	Q5
Waimea Glacial	Tophouse	128,000 - 186,000	Q6
Karoro Interglacial		186,000 - 238,000	Q7
Waimunga Glacial	Harry	238,000 - 310,000	Q8
(unnamed)			Q9
Nemona Glacial	Manuka*	320,000 - 370,000	Q10

2.3.3 Post Glacial Alluvial Gravels

Subsequent to deposition of glacial outwash gravels during the Pleistocene, the Holocene saw the Wairau River and tributaries entrench into the Speargrass Formation, redepositing gravel downstream and supplying new material during a period of alternating aggradation and degradation. This formation is known as the Rapaura Formation (Oxygen Isotope Stage 1 or Q1 – Table 2.1) and is a postglacial fluvial gravel, sand, silt, and clay deposit, derived mainly from erosion of the older Speargrass Formation.

The formation is made up of sub-angular, well-sorted gravel up to cobble size of mostly greywacke gravel at its type location on the Wairau Plains, with schist pebbles present but rare (Brown, 1981).

The Rapaura formation is mapped as Oxygen Isotope Stage 1 and comprises well-sorted flood plain gravels of the current Holocene interglacial period beginning some 14,000 years ago. Brown (1981), has defined an upper and lower unit within the Rapaura Formation with separation based on time of deposition. The lower unit was deposited in the early post-glacial period 7,000 to 14,000 years ago during a period of rising sea level while the upper unit has been deposited since postglacial marine transgression ca. 7000. This is illustrated in Figure

2.5 where fluvially reworked gravels are separated by an aquitard which represents a siltstone-mudstone unit laid down during marine transgression.

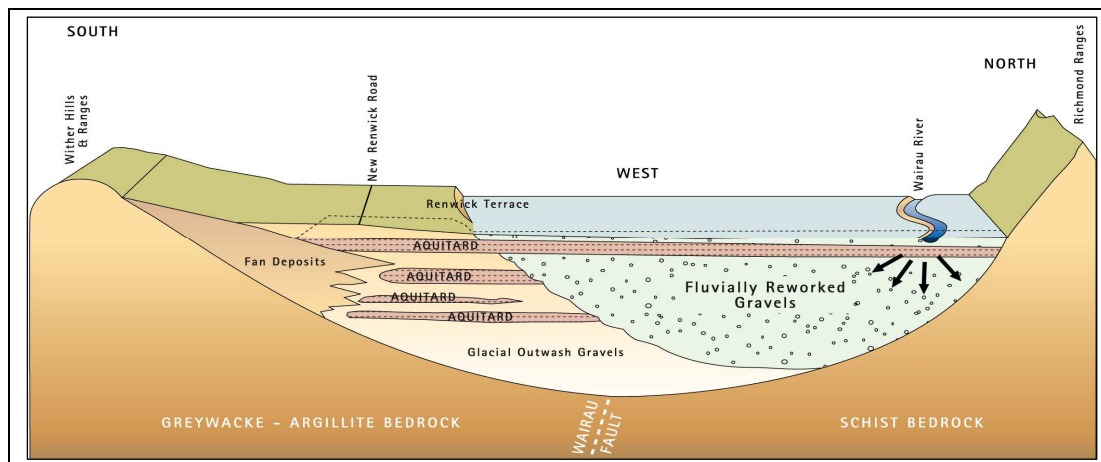


Figure 2.5: Cross-sectional model of Wairau Valley (Source: P. Davidson, pers. comm.)

The modern day surface of the Rapaura Formation is represented by floodplain and fan deposits, however, surface deposits that are still accumulating and subject to movement (river flood channels), are excluded from the Rapaura Formation. The relatively thin deposits of the Rapaura Formation are moderately well sorted gravels which form the Recent floodplain adjacent to the Wairau River and its major tributaries. The gravel is dominantly composed of quartzo-feldspathic clasts. The matrix is not as tightly clay-bound as in the aggradation gravel units. Layers of sand, silt, and clay, commonly less than 1 m thick are widespread (Johnston, 1994).

Worth noting are landslides, which are common on the steeper slopes of the study area. The deposits consist of poorly sorted, silty clay-bound gravel which is widespread but rarely extensive. Although largely of Oxygen Isotope Stage 2, they are mapped as undifferentiated (Begg and Johnston, 2000). The deposits may reach up to 10 m in thickness and are of late Quaternary age.

2.4 GEOMORPHOLOGY

Geomorphic surfaces within the North Bank study area closely correspond to stratigraphy, with each of the major quaternary formations having a representative geomorphic surface. A geomorphic surface is a landform that formed under a given set of conditions and during a

particular amount of time, and within the North Bank study area, principally take the form of aggradational terraces and alluvial fans.

The North Bank has a fluvio-glacial dominated topography with Speargrass Formation outwash gravels associated with a major ice advance (Kumara 2₂) during the Otira glaciation; covering the majority of the North Bank area adjacent to the Wairau and lower level flood plains of the tributary valleys (Suggate, 1990). Erosion took place on a massive scale during this time with eroded debris being carried or pushed down the valley with the glaciers as they advanced. The debris was either retained within the ice of the glacier or carried downriver and deposited as glacial outwash in the melt water issuing from the glacier (Rae, 1988 - Figure 2.6A). As the glaciers retreated, down-cutting by the Wairau River occurred, creating terrace scarps within the outwash gravels (Figure 2.6B) along with aggradation of fluvially reworked gravels corresponding to the Rapaura Formation and more recent alluvium (Figure 2.6C). In this way, older outwash aggradation surfaces are found at higher elevations to younger ones. The present-day product of these processes is a series of fluvial terraces encountered in the North Bank study area, generally parallel to the Wairau River and tributaries.

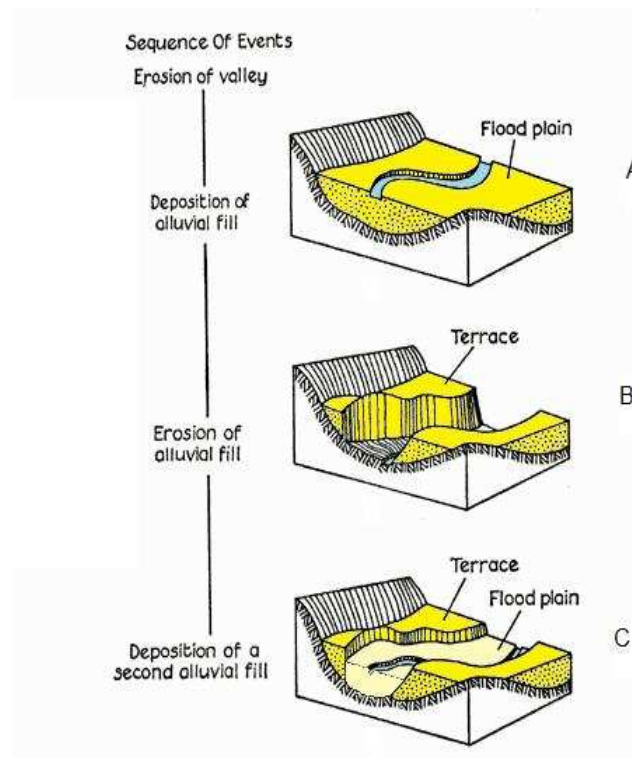


Figure 2.6A-C: Conceptual formation of a river terrace shown in sequence of events. Glacial outwash gravels corresponding to Speargrass Formation are depicted in bright yellow while fluvially-reworked gravels corresponding to Rapaura Formation and modern floodplain gravels are pale yellow in colour. Note: erosion of alluvial fill in 2.6B would not necessarily have occurred completely to bedrock in Wairau or tributary valleys due to significant depth of alluvial fill (Modified from Leopold et al., 1964).

Geomorphology is shown for each of the tributary valleys at their junction with the Wairau River in a series of 1:10,000 maps in relation to ground- and surface-water oxygen isotope values (Figure 5.12, Figure 5.13, Figure 5.14, Figure 5.16, Figure 5.17, Figure 5.18, Figure 6.13, Figure 7.10, Figure 7.11 and Figure 7.12). A prominent 2-4 metre terrace that delineates the Speargrass Formation and Rapaura Formation aggradation surfaces is common throughout.

2.5 CHAPTER SUMMARY

The boundary between the Pacific and Australian tectonic plates is represented by the Wairau Fault, the north-eastern continuation of the Alpine Fault. The North Bank study area sits upon the Australian tectonic plate which slides dextrally northward against the Pacific Plate. This in turn has defined the course of the Wairau River to within the fault angle depression and the overall geomorphology of the study area.

Present in the area is a zone of regional tectonic metamorphic overprinting that has resulted in the formation of Marlborough Schist in the Early or Middle Jurassic. The Marlborough Schist is comprised of strongly metamorphosed Caples Terrane and Rakaia Sub-terrane greywacke and argillite that are mineralogically more diverse than the weakly metamorphosed sedimentary greywacke and argillite of the Pahau Sub-terrane to the south of the Wairau Fault.

Overlying rock basement are Quaternary deposits that relate to the glacial episodes in New Zealand's past. These deposits are (in order of age, oldest to youngest) the Manuka Formation, the Harry Formation, the Tophouse Formation, and the Speargrass Formation, and are responsible for infilling much of the Wairau and tributary valleys while isolated remnants of older deposits (Manuka and Harry Formations) remain high above the valley floor. Post glacial alluvial gravels in the form of Rapaura Formation can be discerned from the older glacial outwash gravels by the marked difference in permeability due to the lower proportion of fines in the matrix, in addition to being at the lowest elevations on the valley floors.

The North Bank has a fluvioglacial dominated topography with a prominent 2-4 metre terrace that delineates the Speargrass Formation and Rapaura Formation aggradation surfaces common throughout.

Chapter 3

HYDROLOGY AND HYDROGEOLOGY

3.1 INTRODUCTION

Defining the groundwater system upon the North Bank is important for planning and resource allocation purposes. Surface water, in the form of high rainfall, perennially flowing rivers and streams, and spring flow, supplies the majority of water for domestic and farming purposes with groundwater generally used in low quantities for the purposes of irrigation. However, there is a call for more use of groundwater for pasture and vineyard irrigation, although at this stage the resulting effects of this proposed usage on both groundwater quantity and quality are unknown. Currently, the nature of the groundwater system on the North Bank is only broadly understood, and the amount of recharge and groundwater storage has also not been precisely quantified. There are only a limited number of wells and many of the wells tend to be concentrated close to the Wairau River, tributary rivers and streams. In addition, there are very few deep wells to provide information about groundwater at depth (greater than 15 metres) making it difficult to accurately define the complete hydrogeological system.

3.2 HYDROLOGY

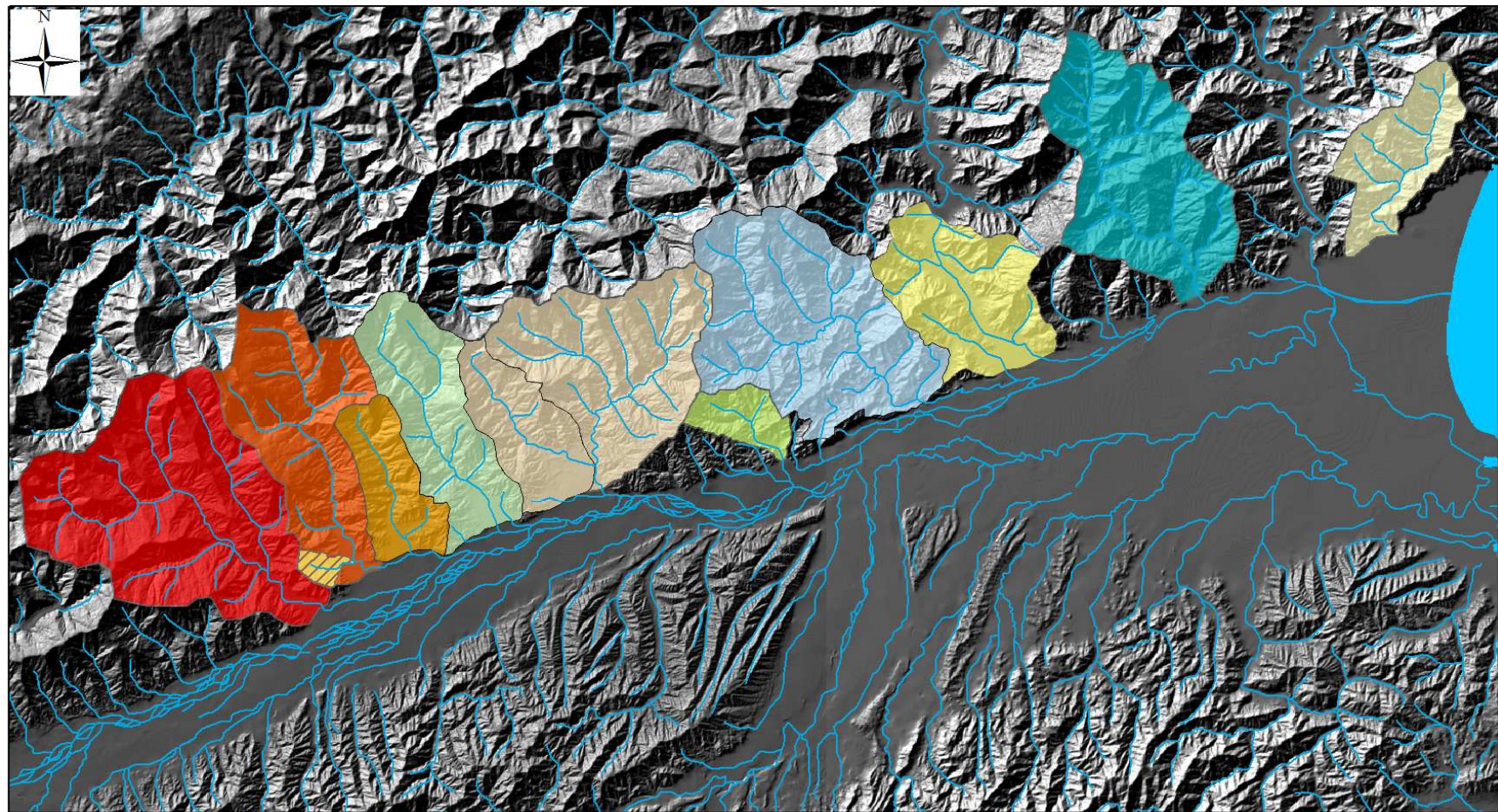
The North Bank receives over 1000 mm of rainfall per year on average (Figure 1.3, Chapter 1), however, despite its relatively high annual rainfall, the average low flow specific discharge to the Wairau River from the North Bank region is only 3.9 l/s/km², significantly less than from catchments elsewhere within the Wairau Catchment. Average low flow specific discharge from upper Wairau catchments for instance, which receive around the same average annual rainfall, is approximately 10 to 20 l/s/km². The apparent anomaly of low North bank specific discharges can be attributed to differences in the geology of the North Bank compared to the rest of the Wairau Catchment (Simpson et al., 1980, and Rae, 1987) and will be discussed later in this chapter. While low flow specific discharge may be small in comparison to upper Wairau Catchments, study of North Bank tributary streamflow indicate that they are still important contributors to stream flow in the mainstem Wairau River (Hudson and McMillan, 2006).

North Bank catchments are characteristically short and steep, also due to the underlying geology, often with catchment width approximating catchment length resulting in large catchment areas (Table 3.1). The drainage pattern of the North Bank catchments considered in this study can be seen in Figure 3.1 with each of the major catchments outlined.

Table 3.1: Major North Bank Catchments and their catchment size in square metres corresponding to polygons drawn in Figure 3.1. Valleys are listed west to east respectively.

Catchment	Major Stream or River	Catchment Size (m²)
Top Valley	Top Valley River	87, 902
Timms Creek	Timms Creek	49, 829
Cat Creek	Cat Creek	18, 815
Burnt Scrub Creek	Brunt Scrub Creek	6,945
Pine Valley	Pine Valley Stream	36, 220
Fabian's Valley	Fabian's Creek	22, 929
Bartlett's Creek	Bartlett's Creek	53, 594
<i>Fabian's & Bartlett's Total</i>		76, 523
Swamp Gully	Swamp Gully Stream	8, 591
Onamalutu Valley	Onamalutu River	69, 074
Kaituna Valley	Are Are Creek	37, 762
Waikakaho Valley	Waikakaho River	57, 201
Pukaka Drain	Pukaka Stream	23, 918

While the Wairau River might not benefit from low flow contribution by North Bank tributaries as much as it does from its headwaters and from Southern tributaries, surface water flow upon the North Bank is significant in the local context with numerous streams and rivers emanating from the major valleys, and spring flow widespread and frequent. Each of the major valleys has a corresponding axial stream or river draining its catchment before its waters join the Wairau River. In the case of Timms Creek and Fabian's Creek, these creeks join either Cat Creek or Bartlett's Creek respectively, before joining the Wairau River. This tendency of North Bank tributaries to flow towards the eastern side of tributary valleys is most likely a reflection of the Northeast tilting of the Marlborough Sounds block that has occurred north of the Wairau Fault, and also the down-valley gradient of the main Wairau Valley (~1/400 gradient - Brown, 1981).



Legend

Rivers	Cat Creek	Bartlett's Creek	Kaituna valley
Top Valley	Pine Valley	Swamp Gully	Waikakaho Valley
Timm's Creek	Fabian's Valley	Onamalutu Valley	Pukaka Drain
Burnt Scrub Creek			

0 5 10 20
Kms

Figure 3.1: Major North Bank Catchments considered in this study. Catchment size is determined by the area of the respective polygon drawn on georeferenced shademodel in ArcMap GIS. Fabian's Valley and Bartlett's Creek are drawn in same colour, as Fabian's Valley drains into Bartlett's Creek (left to right) and the two catchments converge before their waters ultimately join the Wairau River.

3.2.1 Flow Rates

Flow rates for the Wairau River during the study period were recorded by the Marlborough District Council upstream of the study area at Dip Flat and downstream of the study area at Tuamarina, and are presented in Figure 3.2 and Figure 3.3.

The author considers that the flow rate for the Wairau River measured at Dip Flat over the period May 24th 2009 to May 24th 2010 corresponds well to that measured downstream at Tuamarina over the same period, although with subtle points of difference.

The initial point of difference between the sites is the magnitude of flow. The maximum daily flow rate measured at Dip Flat over the period May 24th 2009 to May 24th 2010 was some 224 cubic metres per second (cumecs) while the maximum daily flow rate encountered at Tuamarina was 1140 cumecs. This is a function of their respective positions along the river with the Tuamarina Station benefiting from tributary flow downstream of Dip Flat. This is confirmed upon examination of the median and mean flows from 1961 to 1986 reported for the Wairau River in Table 3.2. The Wairau River at Tuamarina supports both higher median and mean flows than the Wairau upstream at Dip Flat.

Subsequent points of difference are that while high flow events recorded at Dip Flat were also recorded downstream at Tuamarina, their relative magnitude could be quite different. For instance, the high flow event occurring shortly after August 25th 2009 reached a maximum daily flow rate of 142 cumecs at Dip Flat, while the same event reached 675 cumecs downstream at Tuamarina. Additionally, a second high flow event recorded a few days later at Dip Flat reached a maximum daily flow rate of 128 cumecs (less than first event), while at Tuamarina, 1140 cumecs were recorded (greater than first event). In this instance, the Wairau River downstream of Dip Flat must have received tributary flow contribution that Dip Flat itself did not. The reason for this stems from catchment dynamics in that not all high rainfall or flow events occur catchment-wide nor are communicated downstream in a linear way. The variations in pattern from the Wairau at Dip Flat and Tuamarina generally reflect the gradient and distribution of rainfall, including orographic influences associated with particular tributary or subcatchment measurements (Rae, 1988).

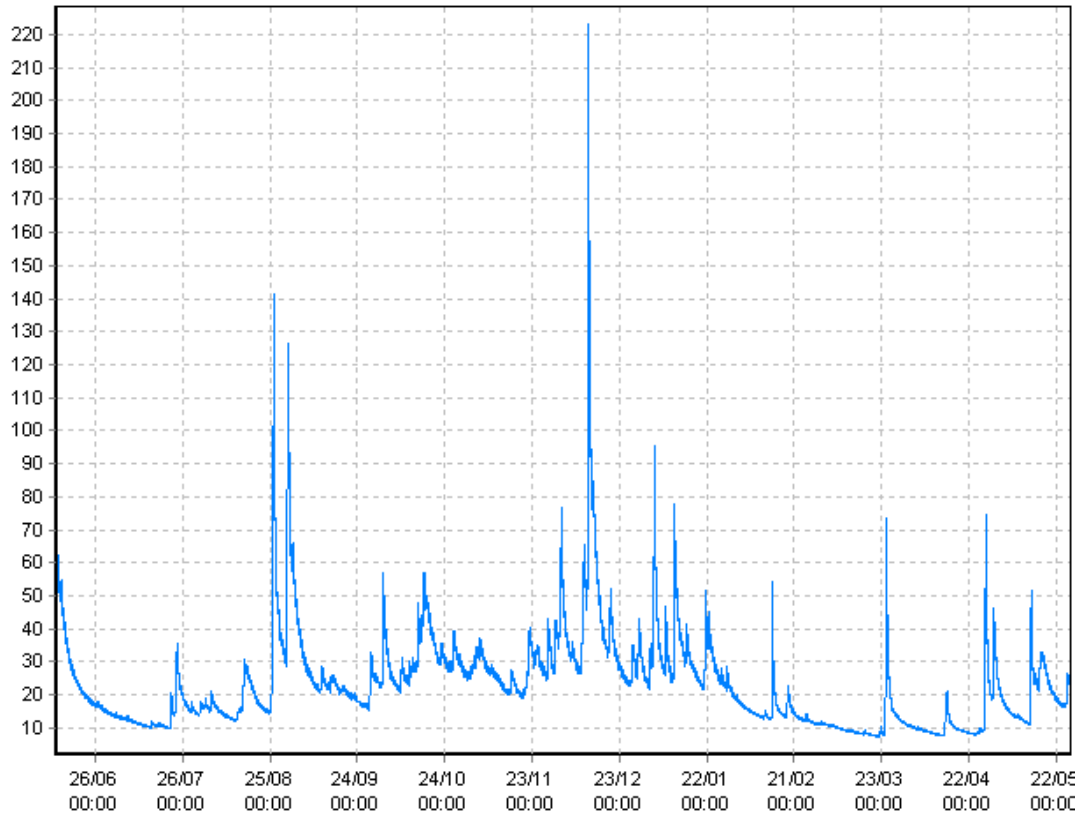


Figure 3.2: Daily flow rate for Wairau River measured at Dip Flat over the period 24/05/09 to 24/05/10. Units are in cubic metres per second.

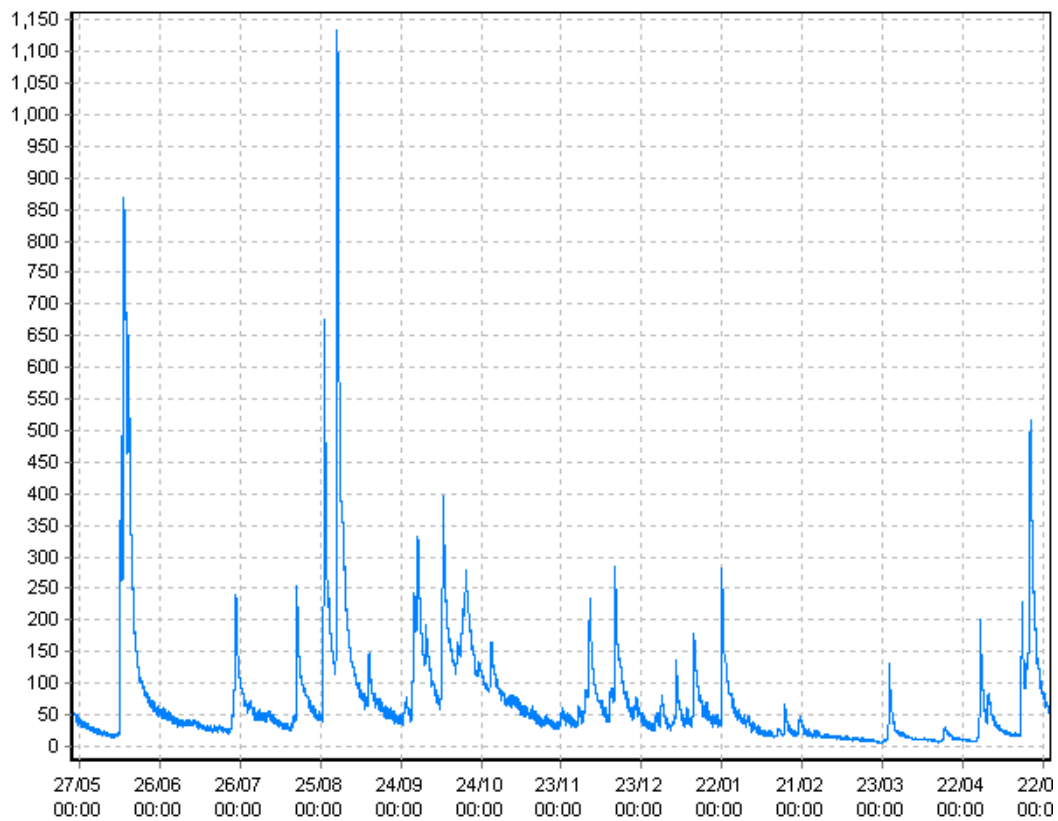


Figure 3.3: Daily flow rate for Wairau River measured at Tuamarina over the period 24/05/09 to 24/05/10. Units are in cubic metres per second.

Table 3.2: Wairau River median and mean flows measured at Dip Flat and Tuamarina 1961-1986 (Rae, 1988)

Station	Median Flow (m ³ /s)	Mean Flow (m ³ /s)
Wairau at Dip Flat	19.5	26.396
Wairau at Tuamarina	72	114.276

Looking in more detail at the North Bank of the Wairau, daily flow rates were also recorded by the Marlborough District Council during the study period for the Onamalutu River at Onamalutu Domain, located approximately halfway up the Onamalutu Catchment (Figure 3.4). Here flow rates are much smaller than those for the Wairau River, as would be expected for a catchment of this size, with flow receding to an average daily flow rate of about 0.5 to 1 cumecs between high flow events. Flow would be expected to increase slightly downstream, however, rainfall distribution is more heavily weighted towards the top of the catchment (see rainfall isohyets, Figure 1.3, Chapter 1). The flow pattern can be taken as typical for North Bank tributaries where input sensitivity is high while base flow is somewhat low. The strong correlation between high flow events in Figure 3.4 and high rainfall events in Figure 3.5 suggest that local rainfall plays a significant role in promoting high flow.

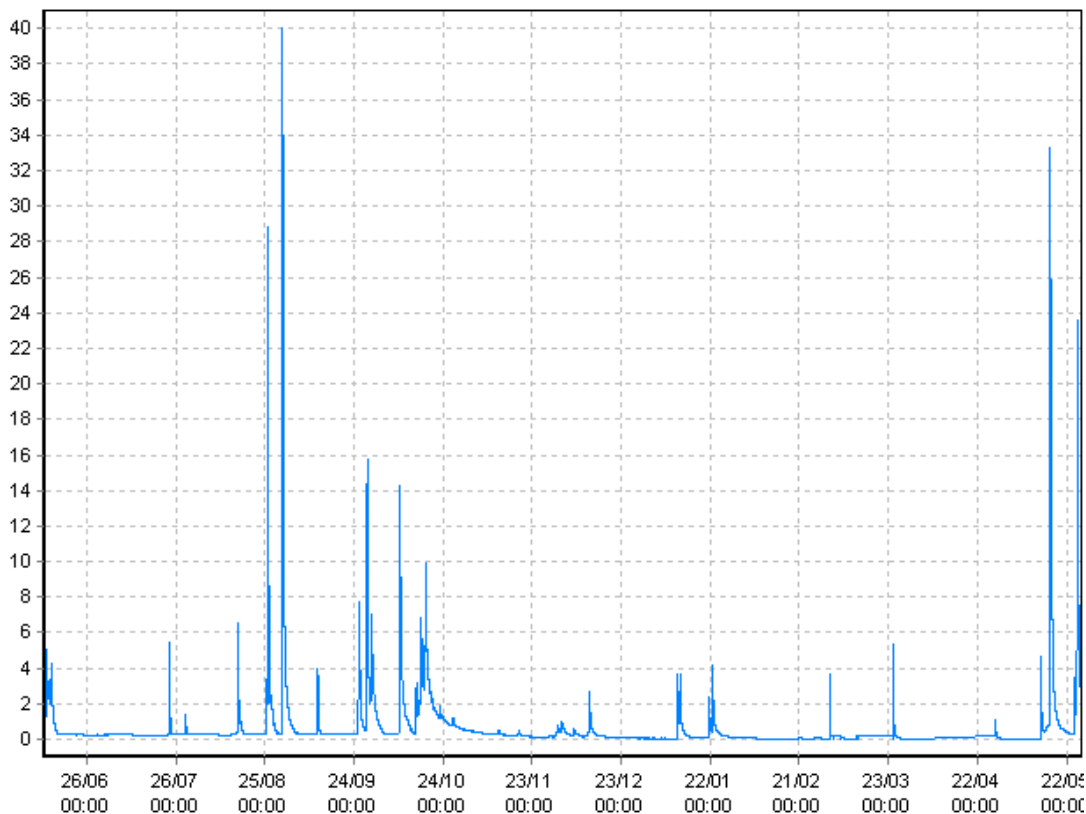


Figure 3.4: Daily flow rate for Onamalutu River measured at Onamalutu Domain over the period 24/05/09 to 24/05/10. Units are in cubic metres per second.

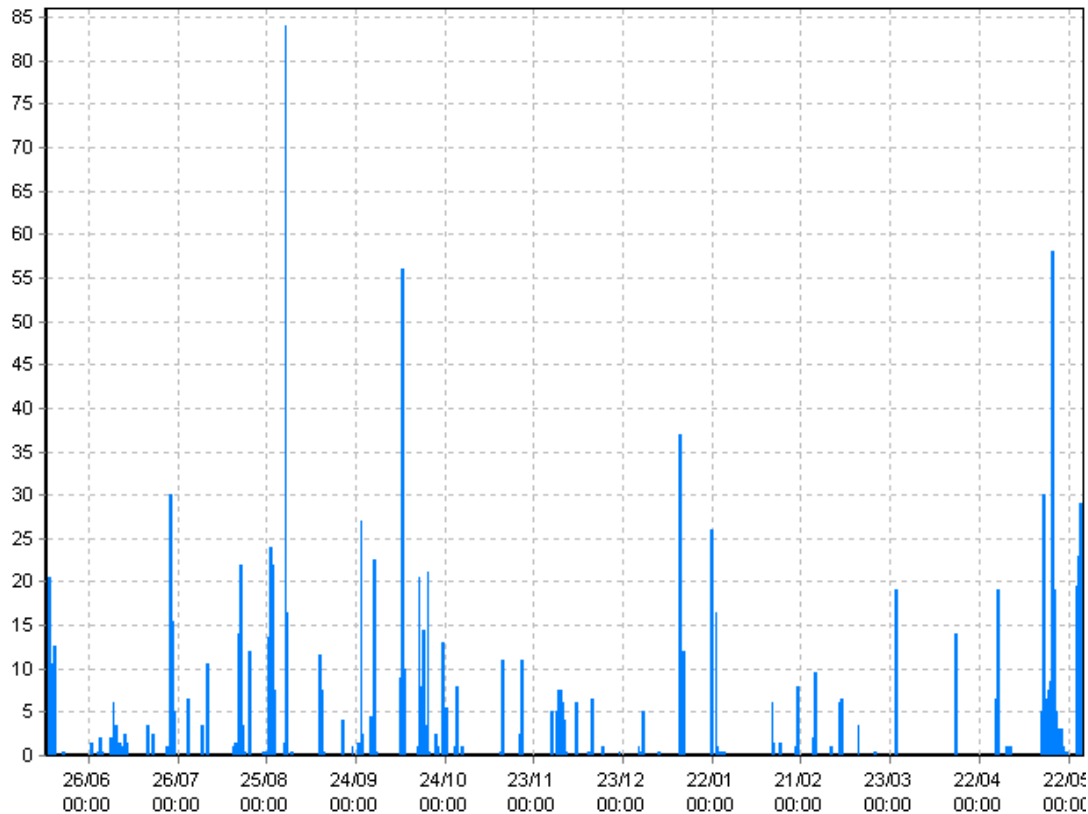


Figure 3.5: Daily rainfall measured at Onamalutu Domain over the period 24/05/09 to 24/05/10. Units are in millimetres.

Evidence of the strong rainfall gradient that exists on the North Bank can be observed in Figure 3.6 where daily rainfall data measured at Top Valley close to the junction with the Wairau River are presented. Data were available over the period 23/12/09 to 27/05/10, during which time rain did not exceed 8 millimetres daily. When compared to rainfall in the Onamalutu Valley over the same period, rainfall is consistently higher in the Onamalutu, where the rain gauge is located closer to the Richmond Range, with a maximum daily value of 56 millimetres reported.

In the absence of rainfall, it follows that base flow must be sustained by groundwater contribution. A study of Top Valley Stream, Timms Creek, Pine Valley Stream and Bartlett's Creek found that even though the summer of 2005-2006 was exceptionally dry, these four streams maintained a flow at their mouths of 1 cumec, 2.1 cumecs, 0.2 cumecs and 0.6 cumecs respectively during low flow conditions (Hudson and McMillan, 2006). While this flow corresponds to a modest 3.9 cumec contribution to the Wairau River, it demonstrates the importance of groundwater in maintaining base flow in North Bank tributaries.

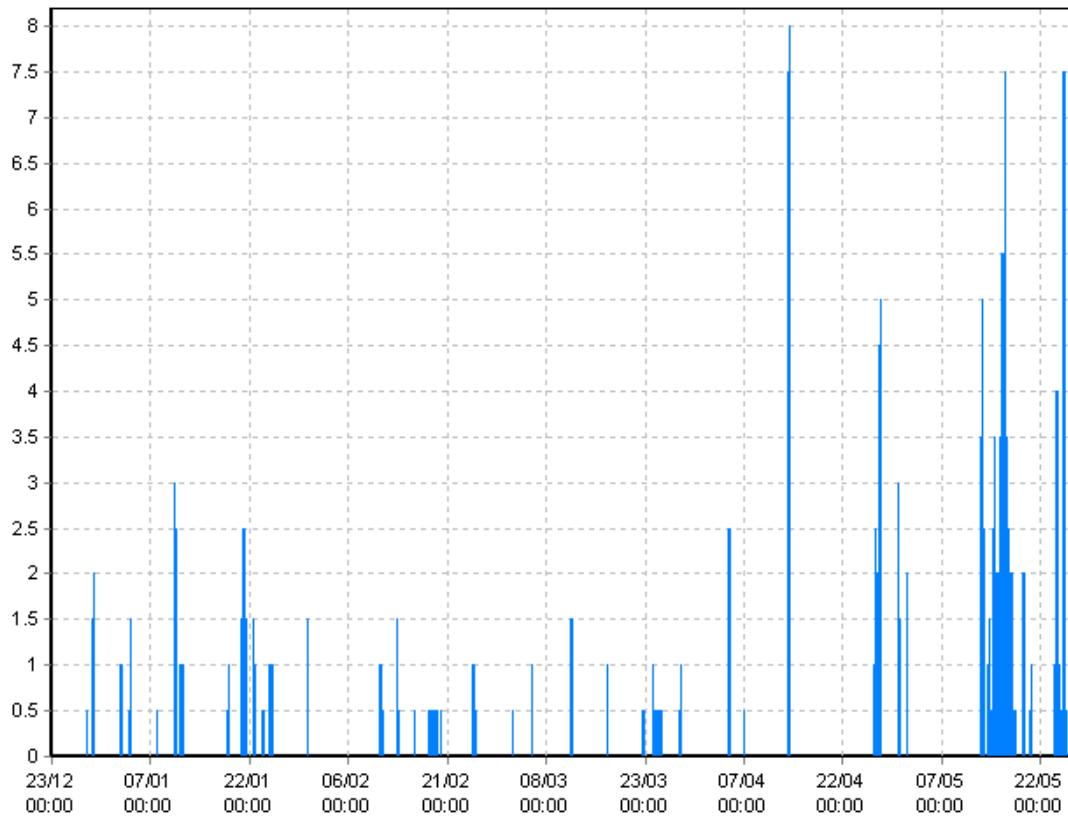


Figure 3.6: Daily rainfall measured at Top Valley over the period 23/12/09 to 27/05/10. Units are in millimetres.

3.2.2 Catchment Discharge Dynamics

From previous work on the Wairau Plain (Taylor et al. 1992) it is known that the Wairau River catchment discharges a mixture of both recently precipitated water and water held in the catchment for several years. Their findings indicate that as much as 50 percent of the river flow (measured at Tuamarina) may be stored in the mountain catchments for, on average, 8 years. The mechanism through which this is achieved is interception of surface water by scree-covered slopes that act as a reservoir so as to slowly release water to the river system, illustrated in Figure 3.7. The influence on water storage and release to the river system by scree deposits can be observed in the contrasting storm hydrographs of Figure 3.8 where the storm response of the Upper Rainbow is significantly less sharp and lower in recession than Begley Creek. Upper Rainbow and Begley are adjacent previously-glaciated catchments where the Upper Rainbow catchment is characterised by a number of large scree and is almost un-forested, while the Begley catchment has less scree and relatively greater beech forest remaining around most of its main and side channels (Simpson et al., 1980).

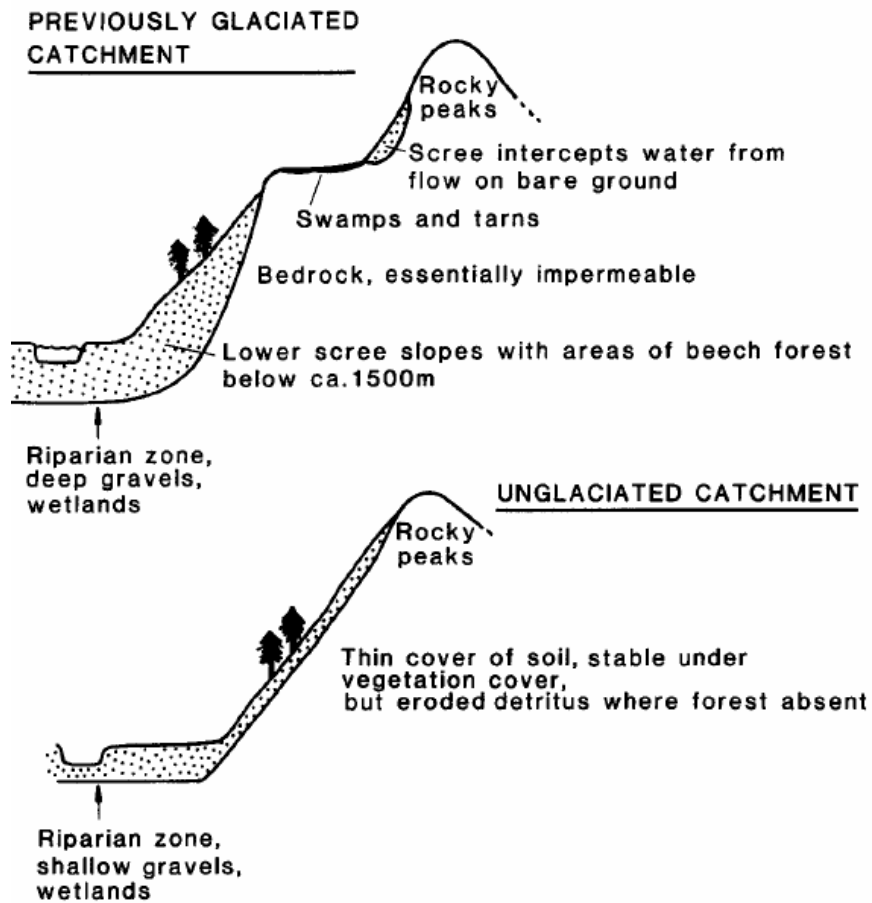


Figure 3.7: Hydrological features of previously glaciated and non-glaciated Wairau mountain catchments (Source: Taylor et al., 1992, after Simpson et al., 1980).

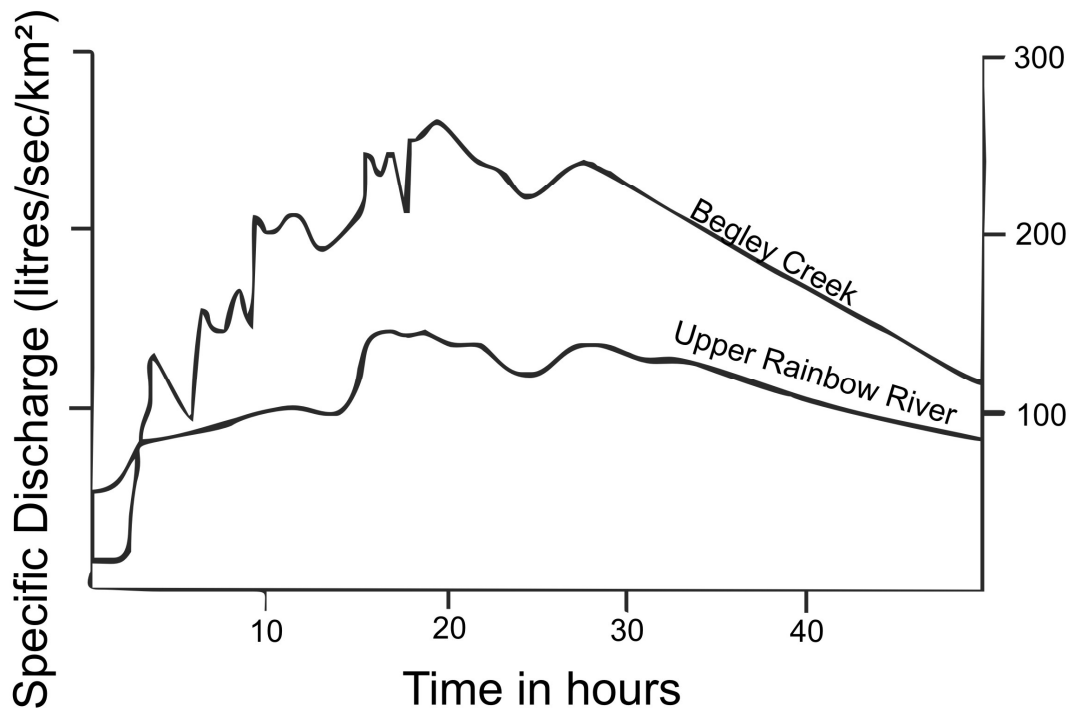


Figure 3.8: Comparative storm hydrograph for Begley (beech forest) and Upper Rainbow catchments (mostly bare with extensive scree cover). Modified from Simpson et al. 1980

The residence time is comparatively short in non-glaciated North Bank tributaries where there is less scree cover than in previously-glaciated mountain catchments. Following the model of Simpson et al. (1980), the thin soils with limited storage in these catchments result in faster addition of surface flow to the river system. A study by MDC in Waikakaho valley reported a mean residence time of groundwater to be 1 year based on age determination using CFC, SF₆, gas, Tritium, geochemistry laboratory results and hydrogeological evidence, while channel flow water was inferred to be only months old (MDC, 2008). The limited amount of scree cover found in North Bank tributaries, where paradoxically high average annual rainfall occurs and low flow specific discharge is anomalously low, indicates that scree plays an important hydrological role. In the absence of deep scree deposits that retain water and slowly release it to the rivers, North Bank catchments with thin soils yield a higher percentage of quick flow and have little water left to contribute in times of low flow.

The hydraulic conductivity (k) of the rock basement and alluvial derivatives, likely plays a negligible role in the hydrology of the North Bank catchments. Megahan (1973) found k -values of $0.2 \text{ m}^3/\text{day}/\text{m}^2$ and $0.98 \text{ m}^3/\text{day}/\text{m}^2$ for schist and a greywacke-equivalent, respectively, determined on the rock matrix. Despite this discrepancy in k -values, in the field, secondary hydraulic conductivity through rock fractures and cleavage would be expected to have greater importance on water migration which could render primary k -values superfluous. In all likelihood, as both schist and greywacke bedrock are essentially impermeable, far greater consideration should be given to their propensity to produce regolith and subsequent scree formation.

3.2.3 River Stage Height and Water Level Observation

No wells are currently monitored on the North Bank with the exception of MDC well 10110 in the Waikakaho Valley (the data of which will be presented in Chapter 5) in view of the fact that historically groundwater demand upon the North Bank has been light. Worth mentioning here is that groundwater levels from the monitored well appear to mirror river stage height within the Waikakaho River. The close relationship between river stage height and groundwater levels is likely to be widespread across the North Bank wherever a hydraulic connection exists between tributary streams and rivers and associated riparian aquifers.

3.3 HYDROGEOLOGY

Relatively little information exists regarding North bank riparian aquifer characteristics such as transmissivity or storage coefficients, due to minor utilisation of the aquifer. In light of groundwater demand increasing since the 1980s through land use intensification and rural residential settlement, further information gathering is timely if not overdue. The somewhat limited numbers of water wells are commonly located near rivers or streams to intercept sub-surface flow associated to or from the river, and only driven to a relatively shallow depth, making complete understanding of the hydrogeological system difficult.

3.3.1 Conceptual model and Cross-sections

Despite a lack of data of aquifer characteristics such as transmissivity or storage coefficients, much has been learnt from experience through geological study, historic well and exploratory drilling for domestic and farming purposes, as well as gold exploration. The distinct geology of the North Bank area is influential in the nature and occurrence of groundwater with a broad conceptual understanding that groundwater must only occur in those lithological units able to host and transmit groundwater. A conceptual model of the hydrogeology of the North Bank is shown in Figure 3.9.

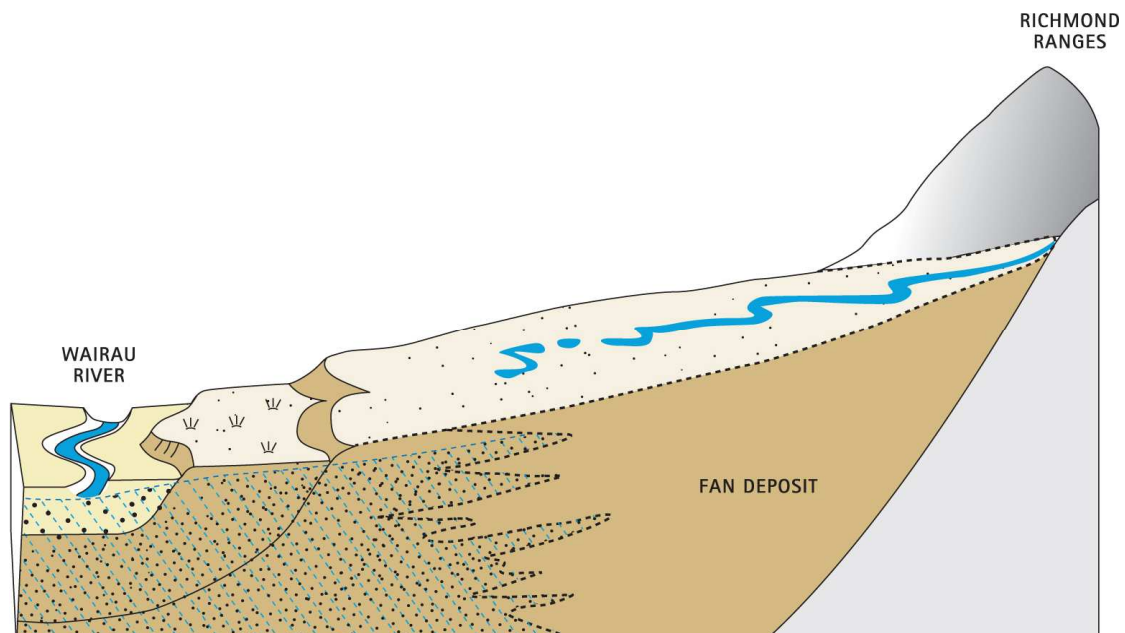


Figure 3.9: Conceptual model of surface hydrology and hydrogeology of the North Bank. The blue hatched area is where groundwaters and surface waters from North Bank tributary valleys mix with waters of the Wairau River. Source: P. Davidson, pers.comm.

Figure 3.9 displays how surface waters drained from the Richmond Range flow out from North Bank tributary valleys at their junction with the Wairau Valley. Constrained by impermeable schist bedrock forming the base and sides of the tributary valley, the surface water instead contributes to spring, stream and aquifer through-flow within the tributary valleys as part of a large integrated hydrological funnel. The fan deposits that spill out into the Wairau Valley form an interactive zone where ground- and surface-waters from the north mix with waters of the Wairau River. The exact spatial extent of this mixing zone is unknown for the majority of the North Bank although will be constrained in subsequent chapters.

Precise aquifer delineation has not been carried out to this point, however, the transition from permeable alluvial sediments to schist bedrock places an obvious boundary on the base of any riparian aquifers. Groundwater is generally present from relatively shallow depth with few confining layers encountered. The North Bank riparian aquifers can therefore be regarded as unconfined water table type aquifers that are hosted within the relatively permeable alluvial sediments present in tributary valleys.

3.3.2 Hydraulic Parameters

Hydraulic parameters of an aquifer are best determined through aquifer tests which are often more involved and expensive than well tests, due to the need for an observation well and longer pumping time. Consequently, few aquifer tests have been conducted on the North Bank. Alternatively, hydraulic parameters such as transmissivity can be estimated from well tests commonly carried out by well drillers upon completion of a new well. Although subject to some uncertainty, estimation of key hydraulic parameters have been undertaken in this report as a general indication of the properties one would expect to encounter on the North Bank.

3.3.2.1 Specific Capacity

Specific capacity is used to define the productivity of an individual well and is calculated by the yield of the well divided by the drawdown (Fetter, 2001). A higher specific capacity value generally indicates a more transmissive lithological unit that the well is drawing water from. Specific capacity is expressed in this text in units of cubic metres per day per metre drawdown.

Sources of error for specific capacity calculation arrive through variability of pumping time, pumping rate, and well construction. Pumping time is often short (less than a few hours) in order to develop the well, and therefore the results may not be representative. A longer duration pump test (conducted over several days) often results in a much larger drawdown and therefore a lower specific capacity. Short term tests also may not detect the presence of hydraulic boundaries, whether they be recharge or conversely, barrier type. Secondly, as the pumping rate increases, up to the maximum yield achievable (typically the maximum rate the well was pumped at rather than the true maximum yield) specific capacity decreases (Driscoll, 1986). Therefore, the sometimes arbitrary pump rate selected will limit the specific capacity calculated. The third source of error, well construction, has a direct bearing on well efficiency through turbulent well losses, and often no more than partial penetration of the aquifer. Both well losses and partial penetration will result in underestimation of the true transmissivity of the aquifer transmissivity at that point (Bal, 1996). In light of all these potential sources of error, specific capacity presented here can only be regarded as a proxy for aquifer transmissivity.

Examination of the relationship between specific capacity and well depth revealed no statistically robust relationship ($R^2 = 0.001$, Figure 3.10) . This is not altogether unsurprising when considering that the majority of wells are drilled to only relatively shallow depth to intercept sub-surface flow associated to or from rivers, as demonstrated in Figure 3.11 where most wells are about 15 - 20 metres deep. Figure 3.11 suggests a very generalised relationship of average specific capacity diminishing with depth, although the very small coefficient of determination (0.002) indicates there is little statistical merit to support such a relationship. In addition, the trend line of median specific capacity runs counter to average specific capacity with median specific capacity peaking at greater depth than the latter. Median data were provided to help eliminate the effect of any very large or very small specific capacity values. Specific capacity upon the North Bank can be therefore be deemed to be highly variable in respect to well depth.

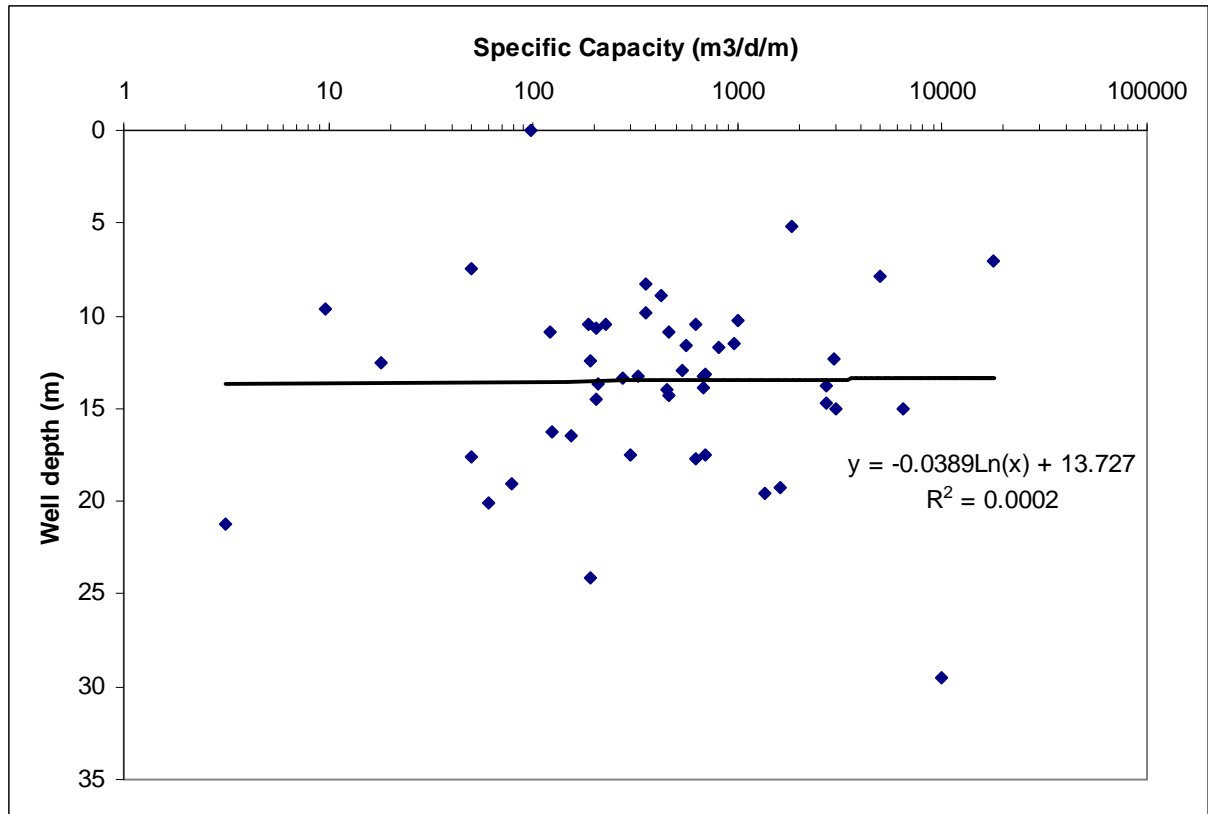


Figure 3.10: Specific Capacity data versus well depth. Fitting a logarithmic trend line yielded the R^2 value of 0.0002 (while a linear trend line gave an R^2 value of 0.001).

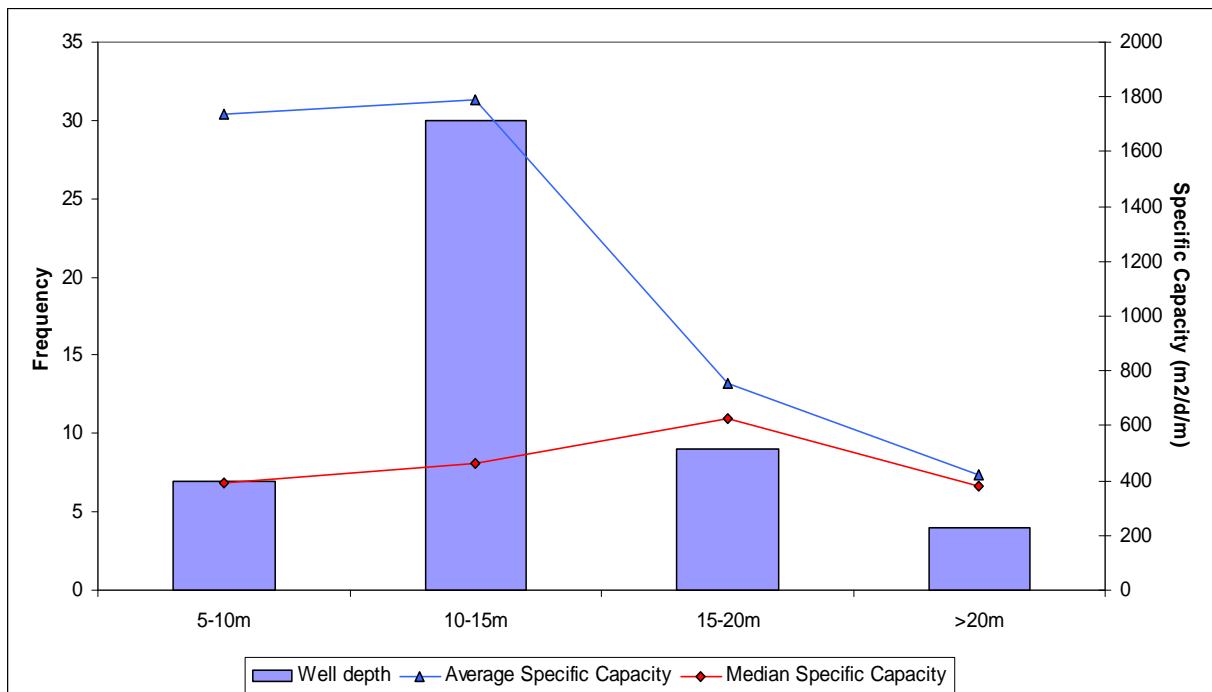


Figure 3.11: Distribution of well depth upon the North Bank for wells with specific capacity data. Average specific capacity for each well depth category and also median specific capacity for each well depth category are displayed.

As well depth on the North Bank is relatively consistent, the major variable is instead specific capacity itself with a range from 3 m³/day/m to 17770 m³/day/m and a high mean of 1546 m³/day/m (as a result of several high specific capacity values). The median specific capacity value is much lower at 501.6 m³/day/m which is perhaps a better reflection of the specific capacity one might expect from a well on the North Bank.

Specific capacity was also compared to distance from the Wairau River in order to see any correlation. Figure 3.12 reveals no statistically robust relationship as around 7 percent of well specific capacity data were found to be attributable to their distance from the Wairau River ($R^2 = 0.07$). Specific capacity, when compared to distance from the nearest channel, whether it be the Wairau River or a North Bank tributary river or stream, gave an even weaker coefficient of determination ($R^2 < 0.01$). The lack of strong statistical relationships between specific capacity and distance to river channels is likely due to the high degree of variability of specific capacity data upon the North Bank.

Specific capacity data for North Bank wells were collected from all months of the year, however, there is a bias towards summer months when most well-drilling is carried out (Table 3.3). Mean specific capacity for the month in which it was tested can be seen in Figure 3.13 with the highest values coming in early to mid springtime (August, September, October). While the time of year may have a bearing on the obtained specific capacity value with highest groundwater levels expected to occur in late winter/early spring, the results presented here are by no means definitive. Mean specific capacity for August is perhaps inflated due to containing the single highest specific capacity value within the study area of 17,770 m³/day found at Beringer Blass Wines Estate 365 metres from the Wairau River upon the historic river bed. The small data set used to calculate each monthly mean should also be taken into consideration with the main finding being that there is a high degree of variability of specific capacity data upon the North Bank.

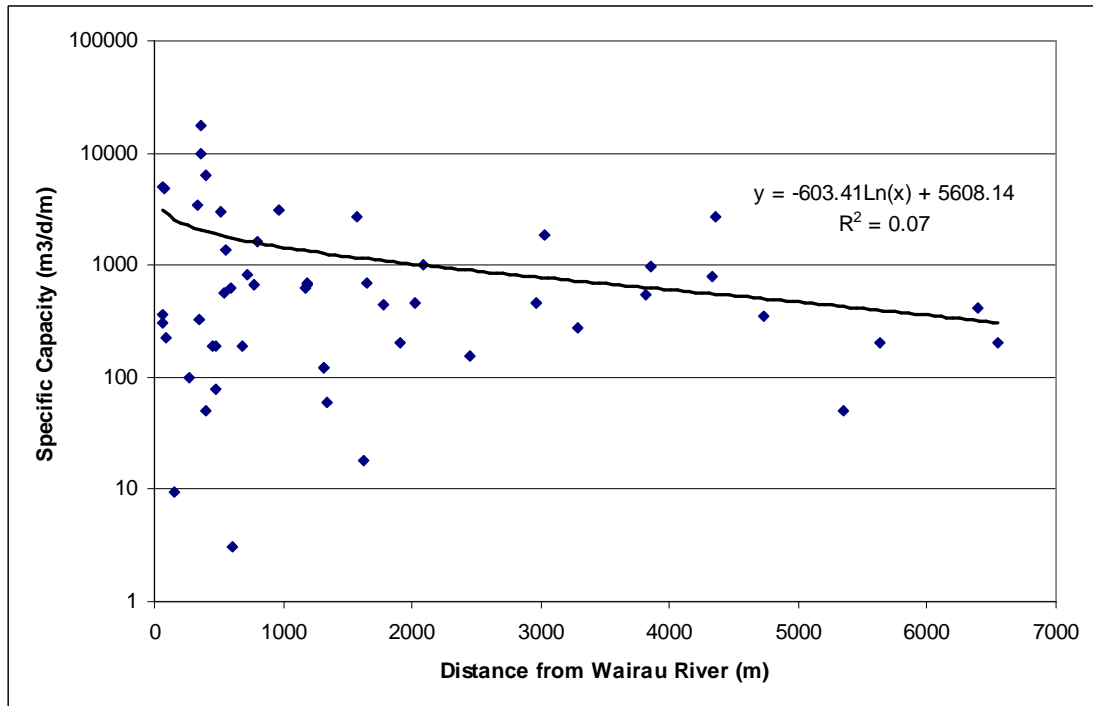


Figure 3.12: Distance from Wairau River versus specific capacity. Fitting a logarithmic trend line gave a R^2 value of 0.07 (while a power trend line yields a R^2 value of 0.0093).

Table 3.3: Mean Specific Capacity for the month in which it was tested, including size of data set to calculate each monthly mean (Number of wells)

Month	Mean Specific Capacity (m ³ /day)	Number of wells
January	558.3	6
February	414.4	3
March	955.2	2
April	316.8	5
May	763.6	4
June	540	3
July	338.4	2
August	5038.7	4
September	2313.4	3
October	3820.8	4
November	1218.3	8
December	1738.6	7

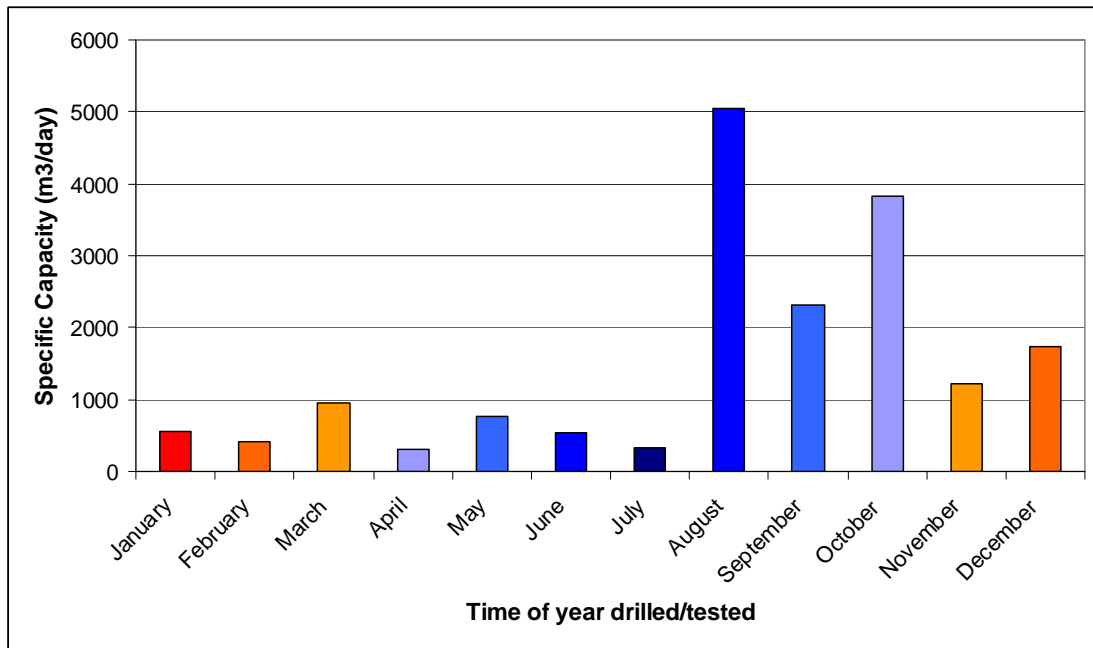


Figure 3.13: Time of year well was drilled and tested versus specific capacity.

3.3.2.2 Storativity

Storativity, also called the storage coefficient, is an indicator of how much water an aquifer releases from or takes into storage per unit surface area of the aquifer, per unit change in head. In an unconfined aquifer such as those on the North Bank, storativity is greater than in a confined aquifer as actual drainage or dewatering of the unconfined aquifer occurs. In comparison, storativity within a confined aquifer is a function of aquifer compression and expansion of water when pumped, and while the pressure is reduced when pumped, the aquifer is not dewatered (Driscoll, 1986). Calculation of storativity is only possible when recording drawdown data from an observation well as part of an aquifer test, and as such, assumed values of storativity must be used in the absence of aquifer test data.

3.3.2.3 Transmissivity

Transmissivity values provide an estimate of possible productivity of groundwater from an aquifer. Transmissivity is the rate water is transmitted through an aquifer through a unit width by the full saturated thickness of the aquifer and a hydraulic gradient of one. It equals the aquifer's hydraulic conductivity (permeability) times the aquifer thickness, expressed by Driscoll (1986) through the equation:

$$T = KD$$

(Equation 3.1)

where T equals transmissivity

K equals hydraulic conductivity

D equals aquifer thickness

Generally, the higher the transmissivity, the more productive the aquifer and the less drawdown observed in the well (Driscoll, 1986). Transmissivity at a point within the aquifer was estimated through the use of specific capacity, and is expressed in units of $\text{m}^3/\text{day}/\text{m}$ which simplify to m^2/day .

Estimation of transmissivity based on specific capacity data is justified on the assumption that transmissivity is linearly proportional to the specific capacity of a well according to a number of different equations, such as the Theis equation (Theis, 1935). Estimated transmissivity values within each valley are summarised in Table 3.3 to Table 3.8, based on the Cooper-Jacob (1946) solution (after Theis 1935), shown in Equation 3.2:

$$\frac{Q}{s_w} = \frac{T}{0.183 \log \left(\frac{2.25Tt}{r_w^2 S} \right)}$$

(Equation 3.2)

where Q is the constant discharge rate [m^3/day]

r_w is the pumped well radius [m]

S is storativity [dimensionless]

s_w is drawdown in the well [m]

T is transmissivity [m^2/day]

t is time [days].

This can be rearranged to find an expression for transmissivity as shown in Equation 3.3:

$$T = 0.183 \frac{Q}{s_w} \log \left(\frac{2.25Tt}{r_w^2 S} \right)$$

(Equation 3.3)

As T appears in the logarithm term as well as being the subject of Equation 3.3, a technique of successive approximation was used to solve for T.

Estimation of transmissivity values are displayed in Table 3.4 to Table 3.9 with a range given for each well. The upper and lower values correspond to storativity values of 0.03 and 0.3 respectively, common storativity values to assume unconfined aquifers range between (Fetter, 2004). From inspection of well logs, nearly all aquifers encountered on the North Bank are inferred to have an unconfined structure.

Table 3.4.: Calculation of Transmissivity for wells within Waikakaho Valley using specific capacity, Wilson's (2008) empirical formula and Bal's (1996) empirical formula. Wells are listed from bottom of valley to top of valley.

Location	Well	Depth (m)	Specific capacity (m ³ /day/m)	Storativity	Transmissivity (m ² /day)	Wilson (2008)	Bal (1996)
Waikakaho Valley	P28w/2953	19.6	98.4	0.03 - 0.3	97 - 77	265	334
	P28w/4650	19.3	1358.4	0.03 - 0.3	1545 - 1280	2105	4145
	P28w/4707	13.2	1608	0.03 - 0.3	1557 - 1874	2405	4874
	P28w/2524	13.9	700.8	0.03 - 0.3	767 - 628	1248	2196
	P28w/2523	13.78	676.8	0.03 - 0.3	739 - 604	1214	2124
	10109	11.46	2712	0.03 - 0.3	3070 - 2532	3635	8050
	10100	11.8	957.6	0.03 - 0.3	1097 - 908	1597	2963
Mean					1267 - 1129	2318	3527
Median					1097 - 908	1915	2963

Table 3.5: Calculation of Transmissivity for wells within Kaituna Valley using specific capacity, Wilson's (2008) empirical formula and Bal's (1996) empirical formula. Wells are listed from bottom of valley to top of valley.

Location	Well	Depth (m)	Specific capacity (m ³ /day/m)	Storativity	Transmissivity (m ² /day)	Wilson (2008)	Bal (1996)
Kaituna Valley	P28w/4132	21.24	816	0.03 - 0.3	924 - 762	1407	2541
	P28w/2971	10.45	3.12	0.03 - 0.3	2.2 - 1.6	17	12
	P28w/4103	12.4	187.2	0.03 - 0.3	201 - 164	440	618
	P28w/3792	24.08	189.6	0.03 - 0.3	184 - 146	444	626
	P28w/3922	10.45	189.6	0.03 - 0.3	193 - 155	444	626
	P28w/3643	19.1	631.2	0.03 - 0.3	632 - 505	1149	1986
	P28w/3809	17.6	79.2	0.03 - 0.3	75 - 59	223	271
	P28w/2859	11.62	50.4	0.03 - 0.3	57 - 47	156	175
	P28w/3918	29.5	566.4	0.03 - 0.3	715 - 604	1055	1790
	P28w/1284	12.35	9813.6	0.03 - 0.3	14275 - 12367	10040	27670
	P28w/3923	17.7	2959.2	0.03 - 0.3	3531 - 2947	3894	8753
	P28w/4765	16.3	624	0.03 - 0.3	682 - 558	1139	1964
	P28w/3086	10.9	122.4	0.03 - 0.3	114 - 90	314	411
	P28w/3369	20.04	120	0.03 - 0.3	112 - 88	310	404
	P28w/3085	10.3	60	0.03 - 0.3	51 - 39	179	207
	P28w/4732	16.5	1008	0.03 - 0.3	1144 - 944	1663	3113
	P28w/3613	9.8	152.88	0.03 - 0.3	147 - 117	375	509
	P28w/3661	11.68	355.2	0.03 - 0.3	389 - 319	730	1144
Mean					1302 - 1106	1992	2935
Median					197 - 158	379	626

Table 3.6: Calculation of Transmissivity for wells within Onamalutu Valley using specific capacity, Wilson's (2008) empirical formula and Bal's (1996) empirical formula. Wells are listed from bottom of valley to top of valley.

Location	Well	Depth (m)	Specific capacity (m ³ /day/m)	Storativity	Transmissivity (m ² /day)	Wilson (2008)	Bal (1996)
Onamalutu Valley	10171	7.9	4828.8	0.03 - 0.3	6362 - 5417	5734	14007
	10179	8.28	4984.8	0.03 - 0.3	6581 - 5605	5879	14441
	P28w/4133	10.5	357.6	0.03 - 0.3	405 - 334	733	1151
	P28w/3353	9.6	225.6	0.03 - 0.3	263 - 218	510	740
	P28w/4269	17.5	9.6	0.03 - 0.3	7.9 - 5.9	42	36
	P28w/4382	12.55	302.4	0.03 - 0.3	327 - 267	642	980
	P28w/4148	17.5	18.24	0.03 - 0.3	17 - 13.4	70	66
	P28w/4271	14.5	688.8	0.03 - 0.3	818 - 682	1231	2160
	P28w/4449	10.9	203.52	0.03 - 0.3	220 - 180	470	670
	P28w/4379	14.25	463.2	0.03 - 0.3	546 - 454	900	1476
	P28w/2266	5.18	458.4	0.03 - 0.3	485 - 394	892	1461
	P28w/4664	13.36	1843.2	0.03 - 0.3	2278 - 1915	2679	5557
	P28w/2989	12.95	273.6	0.03 - 0.3	287 - 232	594	890
	P28w/4515	11.65	540	0.03 - 0.3	611 - 504	1016	1710
	P28w/3083	14.7	801.6	0.03 - 0.3	962 - 804	1388	2498
	10054	7.42	2707.2	0.03 - 0.4	3276 - 2742	3630	8037
	O28w/0057	13.67	50.4	0.03 - 0.3	47 - 37	156	175
	O28w/0119	8.94	206.4	0.03 - 0.3	212 - 170	475	679
	O28w/0221	10.7	420	0.03 - 0.3	466 - 383	833	1343
	O28w/0158	11.1	203.76	0.03 - 0.3	214 - 173	470	671
Mean					1229 - 1045	1417	2937
Median					405 - 334	783	1247

Table 3.7: Calculation of Transmissivity for wells within Langley-dale/Coatbridge area using specific capacity, Wilson's (2008) empirical formula and Bal's (1996) empirical formula. Wells are listed from east to west.

Location	Well	Depth (m)	Specific capacity (m ³ /day/m)	Storativity	Transmissivity (m ² /day)	Wilson (2008)	Bal (1996)
Langley-dale	P28w/4752	13.25	3470.4	0.03 - 0.3	4153 - 3468	4417	10200
	P28w/3191	7	326.4	0.03 - 0.3	355 - 290	682	1055
	P28w/4422	15	17769.6	0.03 - 0.3	22250 - 18757	16049	48926
Coat-bridge	O28w/0215	13.3	3050.4	0.03 - 0.3	3797 - 3197	3989	9012
	O28w/0167	15	679.2	0.03 - 0.3	725 - 590	1217	2131
Mean					6256 - 5260	10118	14265
Median					3797 - 3197	6101	9012

Table 3.8: Calculation of Transmissivity for wells within Bartlett's Creek using specific capacity, Wilson's (2008) empirical formula and Bal's (1996) empirical formula. Well is located on recent floodplain proximal to Wairau River.

Location	Well	Depth (m)	Specific capacity (m ³ /day/m)	Storativity	Transmissivity (m ² /day)	Wilson (2008)	Bal (1996)
Bartlett's Creek	O28w/0252	14	6410.4	0.03 - 0.3	7404 - 6135	7172	18385

Table 3.9: Calculation of Transmissivity for wells within Cat Creek using specific capacity, Wilson's (2008) empirical formula and Bal's (1996) empirical formula. Well is located on upper terrace.

Location	Well	Depth (m)	Specific capacity (m ³ /day/m)	Storativity	Transmissivity (m ² /day)	Wilson (2008)	Bal (1996)
Cat Creek	O28w/0145	11.8	451.2	0.03 - 0.3	493 - 403	881	1439

Estimation of Transmissivity was also carried out using the empirical formulae of Wilson (2008) and Bal (1996) who studied the Wairau Plain and Canterbury Plains respectively. Wilson (2008) defined a linear relationship between transmissivity values and specific capacity values for the Wairau Aquifer in the Riverlands area where:

$$T = 7.05 \times Cs^{0.79}, R^2 = 0.72$$

Bal (1996) defined a linear regression relationship between transmissivity and specific capacity values from over 3,800 wells within the Canterbury Plains area where:

$$T = 10^{(0.96 \times \log(Cs \times 86.4) + 0.61)}$$

Although the lithology upon the North Bank is not exactly the same as the Canterbury Plains, it is useful to calculate transmissivities from Bal's equation to assess its suitability for the North Bank area and as a comparison to the Canterbury region.

Mean estimated transmissivity values calculated from specific capacity are generally quite low at around 1200 m²/day for Waikakaho, Kaituna and Onamalutu Valleys while the Langley-dale/Coatbridge area displays a much higher mean transmissivity at around 5600 m²/day. This could be attributed to both the geology and hydrogeology of the Waikakaho, Kaituna and Onamalutu Valleys. Enclosed valleys such as the Waikakaho, Kaituna and Onamalutu received protection from the Wairau River, both at the time of deposition of postglacial fluvial gravel and subsequent to deposition, which would have otherwise fluvially reworked and sorted sediment to a higher degree than the smaller rivers occupying the valleys. In comparison, the Langley-dale/Coatbridge area is an open, shelf-like area more susceptible to reworking by the Wairau River and consequently, higher rates of transmissivity could be expected from the fluvially-reworked and well-sorted alluvium. Additionally, groundwater within enclosed valleys is also isolated from Wairau River influence and is expected to receive recharge principally from smaller rivers which support lower flow than the Wairau River. Depth to bedrock could be a controlling factor in determining the overlying alluvial thickness and consequently aquifer thickness, with thin water bearing units expected

where alluvium is shallow. However, a considerable depth to bedrock was encountered in Waikakaho Valley (Chapter 6), where transmissivity was low to moderate, which suggests transmissivity is independent of depth to bedrock.

Bartlett's Creek and Cat Creek have only a single well with specific capacity data each, making generalisation difficult. The relatively high estimated transmissivity value of around 6800 m²/day from Bartlett's Creek comes from a well located on the recent floodplain some 400 metres from the Wairau River. Due to the fluvial reworking of the alluvium the well penetrates, the high transmissivity value is unsurprising, however, such high transmissivity is unlikely to exist in this catchment further away from the Wairau River. In illustration of this, the solitary Cat Creek transmissivity value is relatively low at around 446 m²/day, and comes from a well located on the upper terrace some 1780 metres from the Wairau River. Examination of the well log reveals fine silts and clays for much of its depth which points to a low-energy environment that has undergone little fluvial modification.

For all wells, transmissivity values derived by the empirical formulae of Wilson (2008) and Bal (1996) are much higher than those estimated from specific capacity data, particularly those values found using the empirical formula of Bal (1996). Transmissivity estimations are consistently two to four times greater than those estimated from specific capacity data which brings the suitability of this empirical relationship derived from Canterbury well data into question. Transmissivity estimations using the empirical formula of Wilson (2008) are much closer to those values estimated from specific capacity although can be as much as 50 percent greater, particularly for smaller values of transmissivity. For larger values of transmissivity (>4000 m²/day), there is better agreement between the empirical formula of Wilson (2008) and those values estimated from specific capacity. Both sets of transmissivity values are of the same order and can be considered a reasonable match. This would promote usage of the empirical formula to estimate transmissivity, particularly when specific capacity values are high (~3500 m³/day/m or greater).

3.3.2.4 Transmissivity Distribution

Wilson (2008) produced a map depicting the estimated distribution of aquifer transmissivity for the Wairau Plain (Figure 3.14) acquired through transmissivity data obtained from pumping test results for the whole of the Wairau Plain. When comparing North Bank mean estimated transmissivities to those found elsewhere on the plain, the North Bank corresponds most closely to the low-yielding Southern Valleys aquifers and Riverlands aquifer found on

the south side of the Wairau Plain where transmissivity values range from 0 - 500 m²/day and 500 - 1000 m²/day. North Bank mean estimated transmissivities also fall short of those found on the central Wairau Plain where wells tap the highly productive Wairau Aquifer and transmissivity values commonly fall into the 1000 - 5000 m²/day range and above.

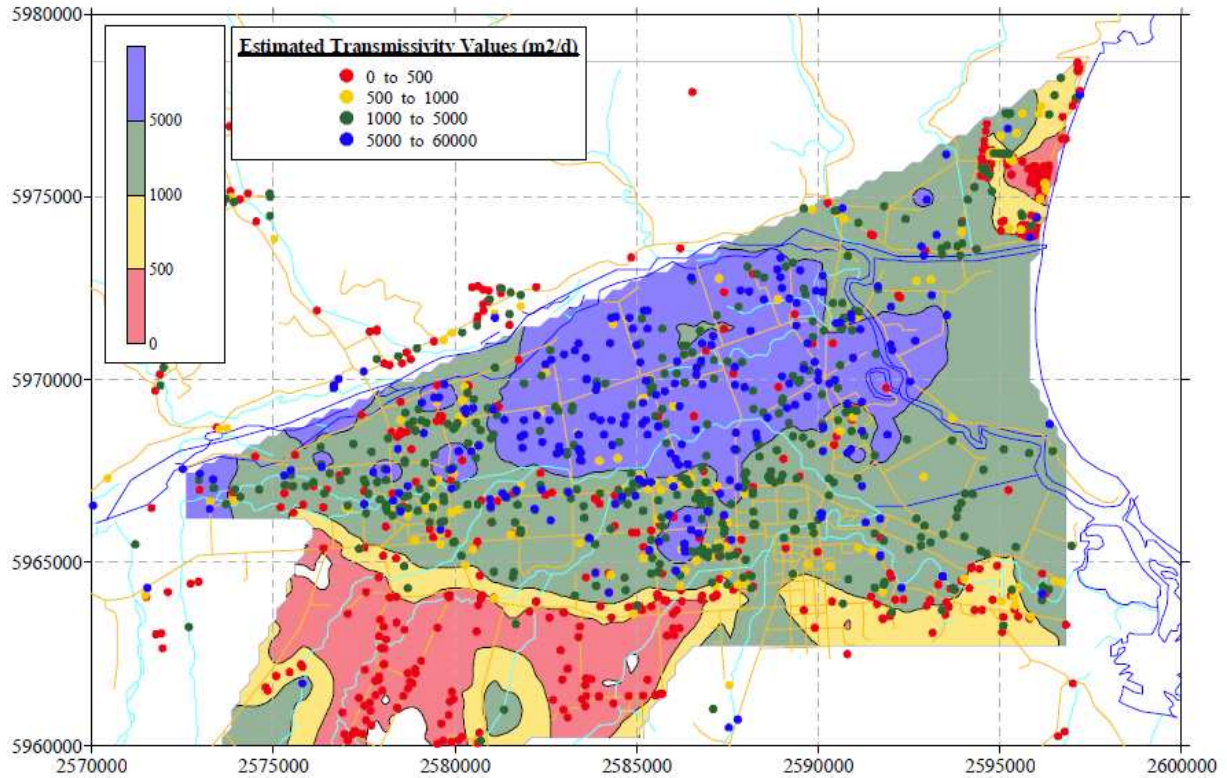


Figure 3.14: Estimated distribution of aquifer transmissivity (m²/day). Source: Wilson, 2008

3.3.2.5 Relationship between Specific Capacity and Transmissivity

The relationship between specific capacity and transmissivity for wells on the North Bank from this study can be seen in Figure 3.14. Specific capacity data are directly related to transmissivity values on a linear basis due to their relationship in Equation 3.2. Fitting a power trend curve allows for an estimation of transmissivity to be made for the North Bank area using the empirical formula:

$$T = 0.63 \times Cs^{1.07}$$

This empirical formula allows estimation of a transmissivity value on the North Bank from specific capacity data without the need for successive approximation to solve for T. The estimated transmissivity value produced is an approximate average of the upper and lower values calculated from specific capacity using storativity values of 0.03 and 0.3 respectively, and as such, is only an approximation due to the assumed storativity value.

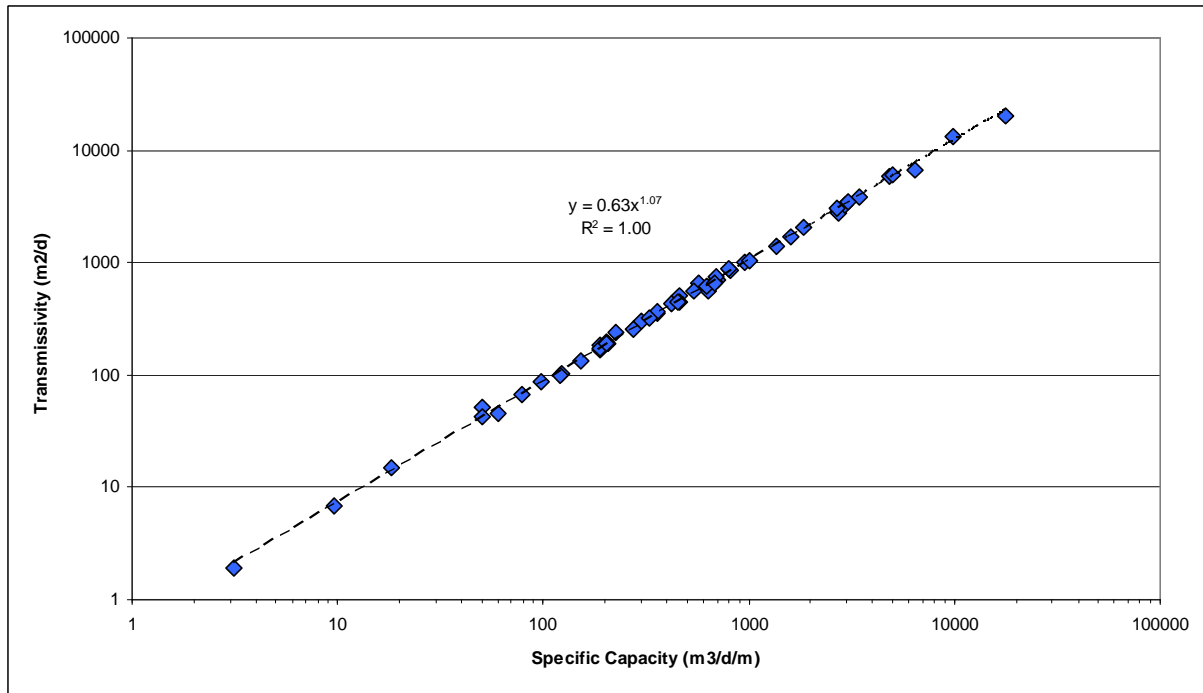


Figure 3.15: Relationship between transmissivity (derived from specific capacity) and specific capacity for the North Bank study area.

The median specific capacity value for the North Bank was found to be 461 m³/day/m (from section 3.3.1). In Figure 3.15, a specific capacity value of 461 m³/day/m approaches the middle of a concentrated cluster of specific capacity values and bisects the overall distribution of specific capacity values well. The median specific capacity value corresponds to a transmissivity value of 455 m²/day using the empirical formula shown in Figure 3.15 and could be regarded as an approximate representative value for aquifer transmissivity on the North Bank. Well specific capacity data is highly variable upon the North Bank, likely due to variability in geology, particularly the degree of fluvial modification of alluvium that host aquifers and the depth to bedrock. Aquifer transmissivity was found to differ markedly in space and, while the limited amount of data restricted seeing such a trend, would generally be expected to increase with proximity to river channels.

3.4 CHAPTER SUMMARY

Although the North Bank has relatively high annual rainfall, the average low flow specific discharge to the Wairau River is anomalously low from this region. This is attributable to the North Bank catchment geology where major scree deposits are absent. In mountain catchments, scree plays an important hydrological role by retaining water and slowly releasing it to the rivers. Perhaps up to half of the river flow (measured at Tuamarina) may be stored in the mountain catchments for, on average, 8 years.

The North Bank hydrological response is relatively rapid in the absence of significant scree deposits, and in conjunction with thin soils with limited storage, water is released quickly from North Bank tributary valleys with little water left to contribute in times of low flow. Groundwater residence time within the Waikakaho Valley for instance is around 1 year while channel flow is only months old (MDC, 2008).

Specific capacity and transmissivity values are relatively low on the North Bank, particularly for enclosed valleys such as Waikakaho, Kaituna and Onamalutu Valleys which receive groundwater recharge from the relatively minor rivers and streams that drain the valleys. The Langley-dale/Coatbridge area is an open, shelf-like area adjacent to the Wairau River from which it would be expected to receive the majority of its groundwater recharge, and displayed higher specific capacity and transmissivity. Not enough groundwater data exists for Bartlett's Creek and Cat Creek, and none at all for Top Valley and Timms Creek, making generalisation about hydraulic parameters difficult.

Transmissivity values derived by the empirical formulae of Wilson (2008) and Bal (1996) were found to be of mixed usefulness. Transmissivity estimations from Bal were consistently two to four times greater than those estimated from specific capacity data, while estimation from Wilson's formula were as much as 50 percent greater, particularly for smaller values of transmissivity. This suggests that empirical formulae derived for other regions such as Canterbury (Bal, 1996) are not suitable for the North Bank, while the empirical formula that Wilson (2008) derived for the Wairau Aquifer is best used when specific capacity values are high ($\sim 3500 \text{ m}^3/\text{day}/\text{m}$ or greater). An empirical formula developed by this study allows estimation of transmissivity from specific capacity without the need for successive approximation.

A transmissivity value of $455 \text{ m}^2/\text{day}$ was found to be an approximate representative value for aquifer transmissivity on the North Bank. This was calculated from the North Bank median specific capacity of $461 \text{ m}^3/\text{day}/\text{m}$. It should be noted, however, that aquifer transmissivity will differ across the North Bank due to season, geological inhomogeneity and distance from river and stream channels.

Chapter 4

HYDROGEOCHEMISTRY

4.1 INTRODUCTION

Groundwater classification based on hydrogeochemical data can help to determine groundwater flow paths, evolution, and origin. Samples collected from different locations can be used to further identify spatial and temporal trends of hydrogeological processes and conditions. In an effort to determine the nature of the waters, a ground and surface water sampling survey, including subsequent hydrogeochemical data collection, was carried out in August 2009. Samples were collected from wells, springs, and streams across the study area revealing important hydrogeochemical characteristics of the waters of the North Bank.

4.2 SAMPLING SURVEY

Ground- and surface water sampling was carried out 3 to 6 August 2009 after delays following significant rain of some 40-50 mm on the North Bank, 22 and 23 July. A week with stable weather was targeted to minimise potential precipitation effects on the data collected. Thirty-five sites were visited over the course of 4 days in order to collect water samples for geochemical and hydrogen and oxygen isotope analysis. Thirty-three sites had a comprehensive suite of chemical analyses performed by Cawthron Laboratories, Nelson as outlined in Table 4.1.

Additional water quality indicators were also tested including total and faecal coliforms, *Escherichia coli* (E.coli), and pH. In addition, each of the samples were analyzed for oxygen and hydrogen isotopic composition at the University of Canterbury's Stable Isotope Laboratory. Two more sites (Are Are Creek and Pukaka Drain) were included to broaden the study area. Although these latter two samples did not have a comprehensive suite of chemical analyses performed due to budgetary constraints, they further extend the isoscape of the north bank. The sampling programme included a range of ground- and surface-water sites to enable interpretation of the origin and flow direction of groundwater on the North Bank, as per the overarching goal of this project.

Table 4.1: Chemical constituents analysed for in Sampling Programme

Major Cations Potassium (K^+) Sodium (Na^+) Calcium (Ca^{2+}) Magnesium (Mg^{2+})	Major Anions Bicarbonate (HCO_3^{2-}) Carbonate (CO_3^{2-}) Chloride (Cl^-) Sulphate (SO_4^{2-})
Minor Cations Ammonia Nitrogen (NH_4^+-N) Iron (Fe^{++}) Manganese (Mn^{2+}) Boron (B^{3+}) Non Ionic Reactive Silica (SiO_2)	Minor Anions Fluoride (F^-) Nitrate Nitrogen (NO_3^--N) Bromide (Br^-) Heavy Metals Arsenic (As)

Sample collection was made in accordance with State of the Environment (SoE) monitoring procedures, both for quality assurance and so that data obtained from this study can also be used for that purpose. Before sampling from a well, it was purged so that at least three times the standing volume of water in the well casing was pumped out to ensure a representative sample of groundwater was collected. During well purging, pH, conductivity and water temperature were monitored on field meters to ensure that no major changes took place and the well had been sufficiently purged. Surface water sites required no purging, but also had pH, conductivity and water temperature monitored in the field. Groundwater samples were taken from the point closest to the wellhead to reduce possible sources of contamination. Dissolved Oxygen (DO) readings were recorded at every site with care taken for the DO probe not to become aerated nor stagnant thus misreporting oxygen present.



Figure 4.1: Portable Grunfos submersible miniature pump powered with a portable petrol generator. Site 016, Well 10100, Waikakaho Valley

Fifteen groundwater samples and 21 surface water samples were collected as outlined in Table 4.2. Where a pump was not already installed, a portable Grunfos submersible mini pump powered with a portable generator was used to sample groundwater (Figure 4.1). This pump had a pumping rate capability of up to 0.5 L/s. The wells were purged of three times the volume of water contained within the well. The purging time was calculated by Equation 4.1 to find the cubic volume of water in litres needed to be purged and then divided by the pumping rate (0.5 L/s) :

$$\frac{\pi \times (\text{Depth} - \text{SWL})(\text{Radius})^2}{1000} \times 3$$

(Equation 4.1)

where Depth equals depth of well
 SWL equals static water level
 Radius equals radius of well

Table 4.2: Sampling sites for ground and surface water sampling survey

Grouping:	Sample:	Date:	Day:	Site:	Water type:
Top Valley / Timms Creek	001	3/08/09	Mon	O28w/0131	Ground water
Bartletts Creek	002	3/08/09	Mon	White irrigation well LOC1071	Ground water
Pine Stream	003	3/08/09	Mon	Offshoot of Wairau River WRR-26	Surface water
Langley-Dale	004	3/08/09	Mon	O28w/0215	Ground water
Onamalutu	005	3/08/09	Mon	Coatbridge Stream CBR-1	Surface water
Kaituna/Are Are Ck	006	3/08/09	Mon	Terrace Spring LDA-1	Surface water
Waikakaho	007	3/08/09	Mon	Swamp Gully Stream SWG-1	Surface water
Pukaka	008	4/08/09	Tues	Wairau River @ SH6 Bridge WRR-3	Surface water
	009	4/08/09	Tues	P28w/3191	Ground water
	010	4/08/09	Tues	Bown reservoir LOC1072	Surface water
	011	4/08/09	Tues	Straight's Stream STR-1	Surface water
	012	4/08/09	Tues	P28w/4906 Skilton Ø2 inch bore	Ground water
	013	4/08/09	Tues	P28w/4907 Skilton domestic bore	Ground water
	014	4/08/09	Tues	P28/4650	Ground water
	015	4/08/09	Tues	Waikakaho Road Bridge WKK-1	Surface water
	016	4/08/09	Tues	10100 Ayling Well	Ground water
	017	4/08/09	Tues	Waikakaho River Bridge Rocky Creek WKK-2	Surface water
	018	5/08/09	Weds	Top Valley Stream at Armchair #8 road TVR-2	Surface water
	019	5/08/09	Weds	Top Valley Stream at North Bank Road TVR-1	Surface water
	020	5/08/09	Weds	Burnt Scrub Creek at Te Rou Road BSC-1	Surface water
	021	5/08/09	Weds	Timms Creek at Cats Creek Road TMC-1	Surface water
	022	5/08/09	Weds	Timms Creek at North Bank Road TMC-2	Surface water
	023	5/08/09	Weds	Pine Stream	Surface water
	024	5/08/09	Weds	Bartlett's Creek BRC -1	Surface water
	025	6/08/09	Thurs	Terracedale Vineyard well	Ground water
	026	6/08/09	Thurs	House & stockwater well	Ground water
	027	6/08/09	Thurs	Shearing shed well	Ground water
	028	6/08/09	Thurs	Spring that flows into stream LOC1073	Surface water
	029	6/08/09	Thurs	Onamalutu River @ domain ONR-2	Surface water
	030	6/08/09	Thurs	O28/0049	Ground water
	031	6/08/09	Thurs	P28/4664	Groundwater
	032	6/08/09	Thurs	Onamalutu River @ bridge ONR-10	Surface water
	033	6/08/09	Thurs	P28/3923	Ground water
	034	13/07/09		10109 (10 inch pumped bore)	Ground water
	035	13/07/09		Waikakaho River Upstream Wratts Stream	Surface water
	036	6/08/09	Thurs	AreAre Creek @ Kaituna-Tuamarina Track	Surface water
	037	6/08/09	Thurs	Pukaka Drain @ Pembers Rd	Surface water

All samples were field filtered with a 0.45 µm membrane and collected in plastic bottles with threaded caps (with preservative where required). Unfortunately, alkalinity was only laboratory tested and not tested in the field by Gran Titrations immediately after taking the sample. As alkalinity is sensitive to T and equilibration with atmospheric CO₂ with time, alkalinity can be expected to have altered somewhat by the time it was laboratory-tested.

Due to budgetary constraints, the sampling survey was carried out only once meaning that temporal variations were not able to be assessed. One exception is the Waikakaho Valley where samples were taken twice, both during the course of an aquifer test, July 2009 and February 2010 respectively.

4.3 ION BALANCE AND TOTAL DISSOLVED SOLIDS

Ions are typically added to groundwater as water travels through the ground and interaction with rock and aquifer materials occurs. This often results in the dissolution of rock minerals to add ions to the water. More than 90 percent of the dissolved solids in groundwater can be attributed to eight ions: Na^+ , Ca^{2+} , K^+ , Mg^{2+} , SO_4^{2-} , Cl^- , HCO_3^{2-} and CO_3^{2-} (Fetter, 1994). A fundamental property of an aqueous solution is that it is electrically neutral, therefore the total number of equivalents of cations should equal the total number of equivalents of anions. This is determined through the following equation:

$$\text{Ion Balance} = ([\Sigma \text{ CATIONS} - \Sigma \text{ ANIONS}] / \Sigma \text{ IONS}) * 100.$$

(Equation 4.2)

The ion balance is therefore expressed as a percentage of the total ion concentration. It is generally considered that 5 percent is a reasonable limit for accepting the analysis as valid (Deutsch, 1997, Freeze and Cherry, 1979). Where the ion imbalance is large, this may indicate that an analytical error exists or an ion was not included in analysis that exists in the solution at a significant concentration.

The majority of the samples in the North Bank area are not in ionic balance. The difference in cations and anions vary from 1.6% to 17 % (Table 4.3). This lack of balance points to either an error in the chemical analysis itself, one or more anions not being analysed, or difficulty in achieving balance in dilute waters. An ion imbalance was found by the 2008 study by the MDC within the Waikakaho Valley where, similarly, dilute waters were encountered and suggest that the difficulty in achieving ionic balance is characteristic of the North Bank, where waters are dilute.

Table 4.3: Major Ion Concentrations (meq/L) for samples collected 3-6 August 2009. Samples are listed from west to east of study area.

Location	Ca	Mg	Na	K	HCO ₃	Cl	SO ₄	F	Σ Ions	Σ cations - Σ anions	Ion Balance %
018 TVR-2	0.245	0.091	0.104	0.005	0.311	0.037	0.035	0.003	0.830	0.059	7.1
001 O28w/0131	0.314	0.123	0.126	0.013	0.361	0.065	0.047	0.003	1.052	0.101	9.6
002 LOC1071	0.314	0.115	0.126	0.005	0.361	0.056	0.052	0.003	1.032	0.090	8.7
003 WRR-26	0.314	0.123	0.126	0.008	0.377	0.059	0.050	0.003	1.060	0.083	7.9
019 TVR-1	0.245	0.091	0.109	0.005	0.311	0.045	0.039	0.003	0.051	0.051	6.0
020 BSC-1	0.245	0.123	0.165	0.015	0.279	0.076	0.070	0.003	0.977	0.120	12.3
010 LOC1072	0.349	0.140	0.113	0.020	0.377	0.073	0.047	0.003	1.123	0.122	10.9
021 TMC-1	0.200	0.081	0.113	0.005	0.246	0.054	0.039	0.003	0.740	0.057	7.7
011 STR-1	0.309	0.123	0.122	0.018	0.344	0.062	0.054	0.003	1.035	0.110	10.6
022 TMC-2	0.235	0.099	0.135	0.013	0.295	0.073	0.043	0.003	0.895	0.067	7.4
023 PNV-02	0.165	0.081	0.126	0.010	0.262	0.039	0.027	0.003	0.714	0.051	7.2
025 O28w/0252	0.549	0.132	1.000	0.026	0.295	1.213	0.054	0.003	3.271	0.142	4.4
026 O28w/0259	0.359	0.197	0.265	0.015	0.393	0.118	0.078	0.003	1.431	0.244	17.0
027 O28w/0258	0.359	0.132	0.391	0.020	0.328	0.395	0.060	0.003	1.688	0.118	7.0
028 LOC1073	0.299	0.115	0.174	0.023	0.311	0.121	0.052	0.003	1.099	0.125	11.3
024 BRC-1	0.220	0.107	0.148	0.018	0.311	0.068	0.029	0.003	0.903	0.081	9.0
004 O28w/0215	0.359	0.156	0.291	0.033	0.344	0.262	0.072	0.003	1.522	0.159	10.5
007 SWG-1	0.354	0.140	0.213	0.010	0.443	0.090	0.039	0.005	1.295	0.140	10.8
005 CBR-1	0.429	0.156	0.565	0.013	0.361	0.592	0.064	0.003	2.184	0.144	6.6
006 LDA-1	0.454	0.156	0.696	0.023	0.377	0.705	0.066	0.004	2.482	0.177	7.1
029 ONR-2	0.180	0.082	0.135	0.015	0.246	0.073	0.025	0.003	0.759	0.065	8.6
030 O28w/0049	0.175	0.082	0.126	0.015	0.229	0.073	0.025	0.003	0.729	0.068	9.4
009 P28w/4752	0.649	0.222	1.218	0.043	0.475	1.241	0.136	0.005	3.990	0.275	6.8
031 P28w/4664	0.235	0.099	0.261	0.015	0.262	0.214	0.031	0.003	1.120	0.099	8.9
013 P28w/4907	0.389	0.148	0.257	0.020	0.393	0.228	0.052	0.003	1.490	0.138	9.3
012 P28w/4906	0.394	0.165	0.231	0.020	0.377	0.226	0.054	0.003	1.469	0.151	10.3
032 ONR-10	0.205	0.091	0.209	0.008	0.262	0.152	0.027	0.003	0.956	0.068	7.1
033 P28w/3923	0.230	0.099	0.252	0.056	0.262	0.203	0.033	0.003	1.138	0.136	11.9
008 WRR-33	0.334	0.123	0.174	0.008	0.377	0.096	0.060	0.003	1.175	0.104	8.8
017 WKK-2	0.220	0.107	0.209	0.018	0.262	0.189	0.033	0.003	1.040	0.066	6.3
016 10100	0.334	0.156	0.696	0.020	0.443	0.677	0.045	0.004	2.376	0.038	1.6
014 P28w/4650	0.319	0.165	0.435	0.028	0.393	0.395	0.039	0.003	1.777	0.117	6.6
035 WKK-3	0.250	0.123	0.331	0.026	0.311	0.310	0.037	0.003	1.391	0.067	4.8
034 10109	0.269	0.132	0.331	0.036	0.311	0.338	0.037	0.003	1.457	0.078	5.3
015 WKK-1	0.279	0.148	0.331	0.020	0.328	0.282	0.043	0.003	1.435	0.122	8.5

Fritz (1994) demonstrates that an average error of ~4 percent can commonly occur in groundwater analysis. Fritz's proposed error can be introduced when alkalinity is analysed in the laboratory and not in the field, as dissolved carbonate phases equilibrate in the sample bottle, before analysis is carried out. In dilute waters, this phenomenon results in an excess of cations relative to anions, such as the North Bank samples display, suggesting re-equilibration of dissolved carbonate phases (primarily bicarbonate in this case) occurred. Aqueous

carbonate (CO_3^{2-}) was omitted from the ion balance calculations presented in Table 4.3 as within the pH range encountered on the North Bank, bicarbonate is expected to be the dominant carbonate species with CO_3 being three-to-four orders of magnitude smaller in concentration than HCO_3^- and unlikely to affect ion balance in any significant way (T. Horton pers. com. 2010).

Johnson et al. (1979) found a lack of ion balance in acidic waters. Although, as the pH of the sampled waters was reasonably neutral (field values ranged from 6.2 - 7.8), this can be eliminated as the cause of lack of ion balance.

Fritz (1994) describes the difficulty in achieving a good ion balance in dilute groundwaters with low Total Dissolved Solids (TDS). This is because small errors become more pronounced when the denominator (sum of the cations and anions) is small in the ion balance equation. Given the dilute nature of all the water samples studied here, it is possible that the lack of ionic balance is a result of their low ionic load. It is also possible that one or more ionic species have not been identified. However, as a lack of ion balance is expected of waters with low ionic concentrations, their dilute nature is more likely to be the cause of imbalance.

A weak negative covariation between ion imbalance and TDS is present in the water sample (Figure 4.2), consistent with the interpretation that dilution is at least partly responsible for the lack of ion balance. Nevertheless, the coefficient of determination reveals only 9 percent of ionic imbalance can be explained by TDS data. Thus, the most likely reason for the relatively high ion imbalance is magnification of the analytical errors associated with dilute hydrogeochemical datasets.

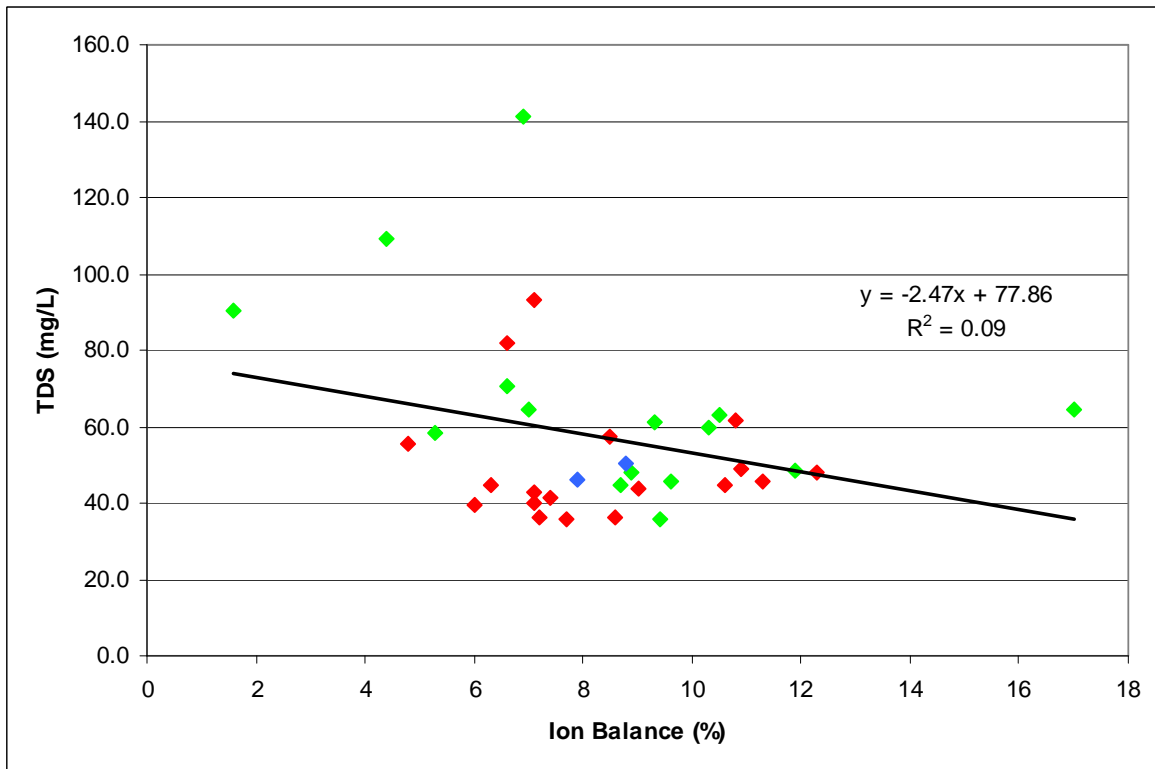


Figure 4.2: Total Dissolved Solids versus Ion Balance. Red data points are surface water sites and green data points are groundwater sites. The two blue data points are Wairau River samples. Data points which plot closer to the y-axis have a smaller calculated ion imbalance.

Figure 4.3 depicts the TDS across the study area with TDS values displayed west to east (left to right) respectively. The range of TDS values was 35.8 mg/L to 141.2 mg/L. Surface water is more dilute with average TDS for groundwater samples being 66.3 mg/L while average TDS for surface water samples was 49.4 mg/L. The higher average for groundwater may be a reflection of both longer residence time of groundwater and further water-rock interaction by groundwater compared to surface water. The two highest TDS samples (O28w/0252 and P28w/4752 - both groundwater wells), came from sites currently used for viticulture.

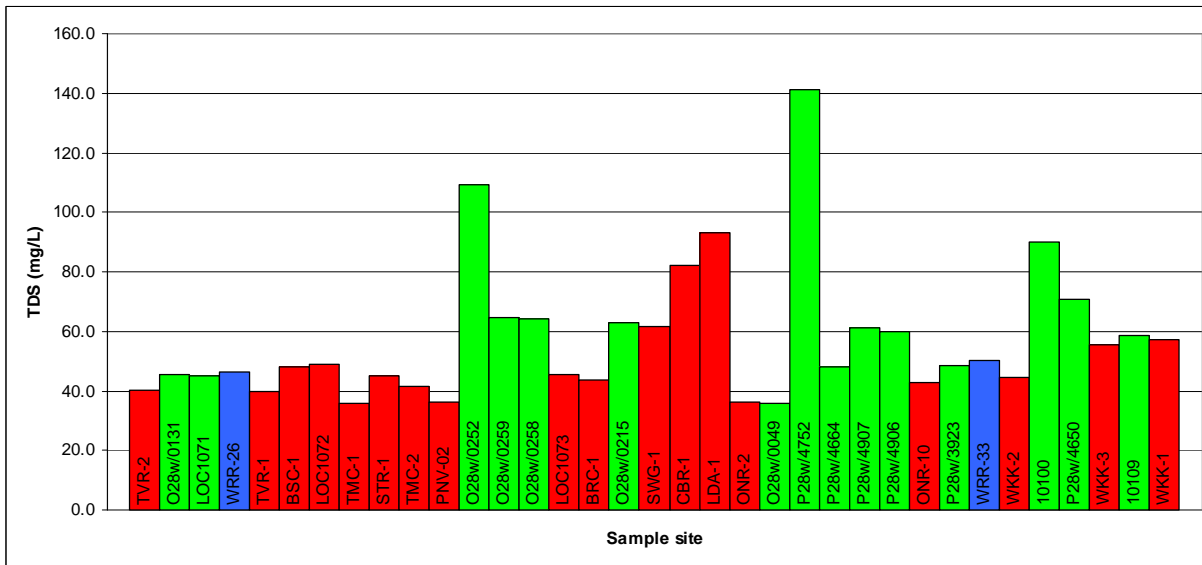


Figure 4.3: TDS across study area. Red columns denote surface water sites while green columns are groundwater sites. Blue columns are Wairau River samples. Sample sites are displayed west to east respectively.

Generally, the TDS amounts are quite consistent with no obvious trend discernable. The lower Wairau River sample shows a slight increase in TDS compared to the upstream Wairau River sample (46.2 mg/L compared to 50.1 mg/L respectively). This slight increase suggests that either any added ions from waters from tributary flow are minimal or have little influence on the Wairau River due to the sheer volume of flow in the Wairau River and consequent dilution.

Timms Creek, Onamalutu River and Waikakaho River display higher TDS at the base of their catchments than higher in their catchments which is probably a function of the addition of ions as water travels downstream. Surface water sites from the Langley-dale/Coatbridge area exhibited elevated TDS compared to other surface water sites (SWG-1, CBR-1, and LDA-1 in particular). This could be an indication of groundwater rising to the surface which adds dissolved salts to surface water (P. Davidson pers. comm., 2010). However, consideration must be paid to the greater agricultural activity within the Langley-dale/Coatbridge area per square unit area compared to tributary values. While a large proportion of this area is low-lying and flat, other North Bank tributary valleys have a narrow and enclosed nature with high, steeply dipping rock boundaries that results in a large proportion of the catchment being unsuitable for pastoral grazing.

Examination of mean chemical concentrations for the unconfined Wairau aquifer within the Wairau Plains reveals a similarly low TDS content (59.6 mg/L) with TDS increasing within the aquifer upon confinement (87.3 mg/L) towards the coast (Close, 2008). The low TDS content on average for the unconfined Wairau aquifer is due to the significant recharge by the Wairau River resulting in fresh, fast-moving groundwaters. In comparison, the dilute nature of North Bank groundwater is due to high rainfall and similarly a fast rate of groundwater flow.

4.4 GROUNDWATER EVOLUTION

Groundwater, as it travels through a sedimentary basin, displays variation in the concentration of ions as it evolves through a sequence towards seawater chemistry (Chebotarev, 1955). This process of evolution operates through most major ion concentrations increasing and hence TDS increasing with groundwater age due to mineral dissolution reactions occurring during water–rock interaction. Bicarbonate anions dominate in young, shallow water while chloride anions dominate older, deeper water. Freeze and Cherry (1979) divided the groundwater evolution sequence into three zones as outlined in Figure 4.4 (where the dominant anion is bicarbonate, sulphate or chloride respectively). New Zealand groundwater rarely evolves past the HCO_3^- stage in the Chebotarev Sequence (Rosen, 2001).

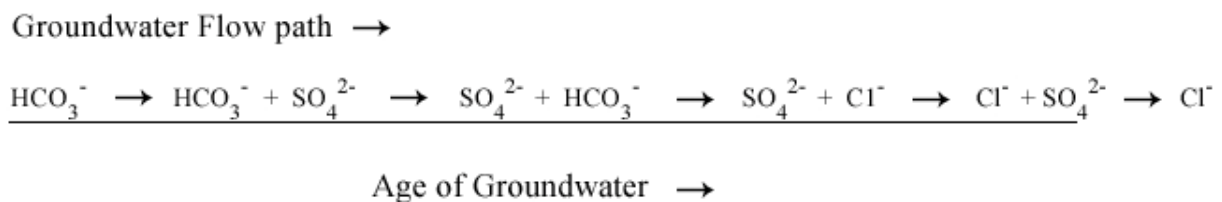


Figure 4.4: Chebotarev sequence showing the anion evolution of groundwater towards the chemical composition of seawater which is largely controlled by the length of the flow path and the age of the water (Freeze and Cherry, 1979)

Contrasting ionic concentrations are also indicative of the flow path water has taken as certain lithologies are more conducive to releasing various minerals than others. The groundwaters of the North Bank fall into the zone where HCO_3^- is dominant with associated low TDS, which indicates that active groundwater is flushing through well-leached rocks (Freeze & Cherry, 1979). This is consistent with North Bank rock basement, formed under conditions of high temperature and pressure, and in conjunction with high rainfall and strong weathering, having

minerals not as easily dissolved in groundwater (Cunliffe, 1988). In addition, the process of converting greywacke to schist has resulted in many of the minerals becoming chemically locked up in stable materials such as mica (Simpson et al., 1980). The dominance of HCO_3^- in waters sampled, and with associated low TDS, indicates that not only is water young within the context of the Chebotarev Sequence, but also that North Bank and Wairau catchment lithologies are slow to weather and fairly insoluble (Freeze & Cherry, 1979).

4.5 MAJOR CATIONS

4.5.1 Calcium

Natural sources of calcium reported by Hounslow (1995) include dissolution of carbonates (aragonite, calcite and dolomite), sulphates (gypsum and anhydrite), fluorite, plagioclase feldspars, pyroxene and amphiboles. However, given the geology of both the North Bank and the Wairau catchment's headwaters, several of these sources can be discounted. Consisting of tz IIIA of the Caples Terrane, the rocks upon the North Bank are dark grey, graphitic, pelite-dominated schists, and at tz IIIB-IV of the Torlesse Terrane, strongly segregated, psammitic quartzofeldspathic micaschists and greenschists (Johnston 1994). The common mineral assemblages are quartz - albite - muscovite - chlorite \pm titanite + pumpellyite \pm actinolite \pm clinozoisite \pm stilpnomelane (Nicol & Campbell, 1990; Mortimer, 1993). It follows that calcium could be sourced from any plagioclase feldspar, pumpellyite, actinolite, or clinozoisite present, as well as any detrital pyroxene or amphiboles. It should be noted, however, that calcium from silicate minerals that are produced during metamorphism are generally low in concentration as the rate of weathering is slow (Hem, 1992), as seems to be the case here. Weathering of Torlesse Terrane rocks at the headwaters of the Wairau catchment would also account for the Ca- HCO_3^- dominance, bearing in mind the Torlesse Terrane is composed of quartzo-feldspathic clasts which are relatively inert.

Calcium concentration ranged from 3.3 mg/L to 8.6 mg/L. Two sites had higher calcium concentrations of 11 mg/L and 13 mg/L, however, both these sites were situated at vineyards where possible influence from fertilisation is taking place due to elevated sodium, potassium and chloride levels, stronger presence of trace metals (Fe and Mn) and high electrical conductivity. Despite the relatively low concentration of calcium ions across the study area, calcium was the dominant cation for all waters sampled which is common for New Zealand waters and characteristic of Marlborough (Rosen, 2001). A mean calcium concentration of

8.2 mg/L and 19.5 mg/L for the unconfined Wairau aquifer and Southern Valley aquifers respectively is reported by Close (2008), both of which are greater than that of the North Bank (6.2 mg/L) and attests to both the dilute nature of the North Bank waters and the dominance of calcium as a cation in Marlborough groundwaters.

4.5.2 Magnesium

Natural sources of magnesium include dolomites and silicates (olivine, pyroxene, amphibole and mica). With limestone absent in the field area, silicates such as pyroxene, amphibole and mica are most likely to be the source of any natural magnesium present.

Magnesium concentration ranged from 0.98 mg/L to 2.7 mg/L. The two vineyard sites where possible influence occurred from fertiliser use had magnesium concentrations of 1.6 mg/L and 2.7 mg/L. Rae (1988) found a mean magnesium concentration of 35 mg/L and 5.32 mg/L for South Bank streams while Close (2008) found a mean of 2 mg/L for the unconfined Wairau aquifer, both of which are greater than that of the North Bank (1.5 mg/L). A general trend of increasing magnesium with increasing calcium has been noted as part of New Zealand's Groundwater Monitoring Programme (Rosen 2001). This North Bank study found a moderately strong correlation of 66 percent as shown in Figure 4.5.

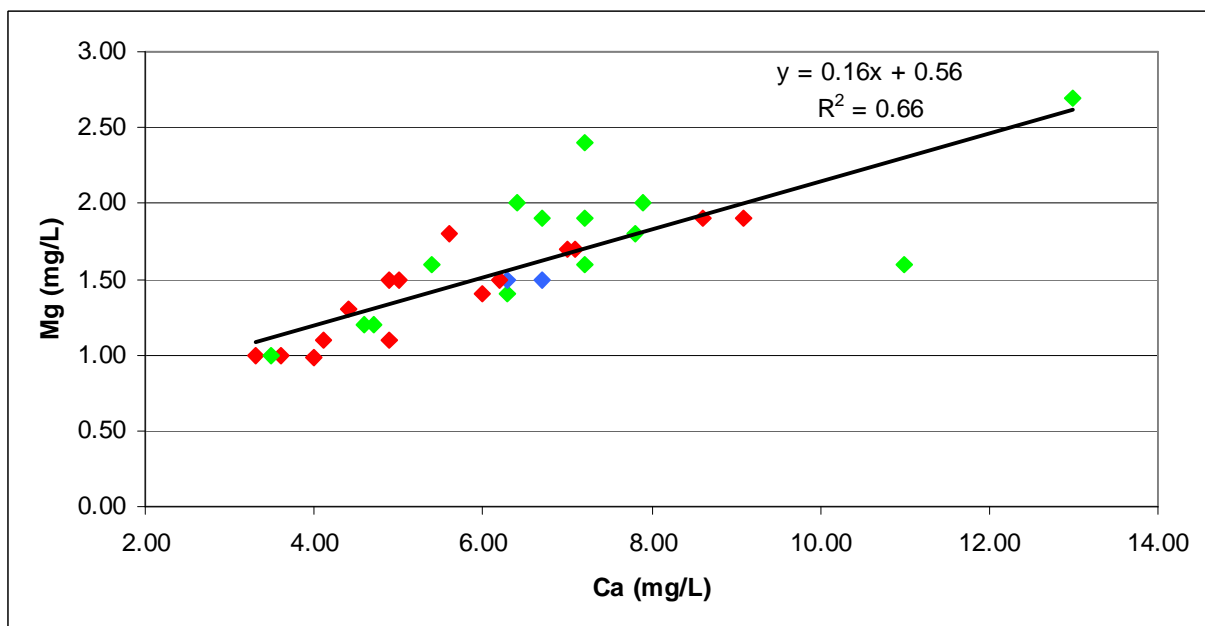


Figure 4.5: Calcium versus magnesium for the North Bank study area. Red data points are surface water sites and green data points are groundwater sites. The two blue data points are Wairau River samples.

4.5.3 Sodium

Natural sources of sodium include sea spray, geothermal springs, plagioclase feldspar (albite and nepheline) and ion exchange reactions with Na-montmorillonite clays. While Rosen (2001) reports sodium and chloride as not generally being dominant ions in fertilisers, they may be important anthropogenic contributors to TDS in this setting.

Sodium concentrations ranged from 2.4 mg/L to 28 mg/L with the two highest values (23 mg/L and 28 mg/L) found at vineyards where possible influence is taking place from fertiliser application. All samples were well below the aesthetic water quality guideline value for drinking water of 200 mg/L which is the threshold for taste (MoH, 2005). A mean value of 29 mg/L and 10.62 mg/L was found by Rae (1988) for the South Bank and Wairau Plain respectively which demonstrates the dilute nature of the North Bank which had a mean value of 6.8 mg/L. A trend of sodium concentration from west to east yielded a R^2 value of 0.1 which suggests sea spray contributes only a minor amount of sodium.

4.5.4 Potassium

Natural sources of potassium include from potassium feldspar, mica particles, and illite or other clay minerals. Anthropogenic sources of potassium include fertilisers and animal waste although plants utilise the majority of potassium from fertilisers and clay mineral reactions in the soil zone take up the remainder. Potassium is generally low in New Zealand aquifers due to sinks in the soil zone and aquifers that remove large amounts of potassium from solution. Potassium concentrations are also typically low in groundwater that also has low sodium levels (Rosen, 2001).

Potassium concentrations ranged from less than 0.2 mg/L to 2.2 mg/L. The two highest values (2.2 mg/L and 1.7 mg/L) were encountered at vineyard sites (well P28w/3923 situated at Kaituna Hills and well P28w/3191 in the Langley-dale area). Almost all other sites had only minor amounts of potassium present (<1 mg/L). The mean potassium concentration for the North Bank was 0.73 mg/L which is similar to a mean value of 0.8 for both the unconfined Wairau Aquifer and Southern Valleys aquifers (Close, 2008). Only the Deep Wairau Aquifer has a larger potassium concentration with a mean of 1.3 mg/L which is a function of the much longer residence time (oldest water sample dated as 38,000 years old) and greater chemical evolution.

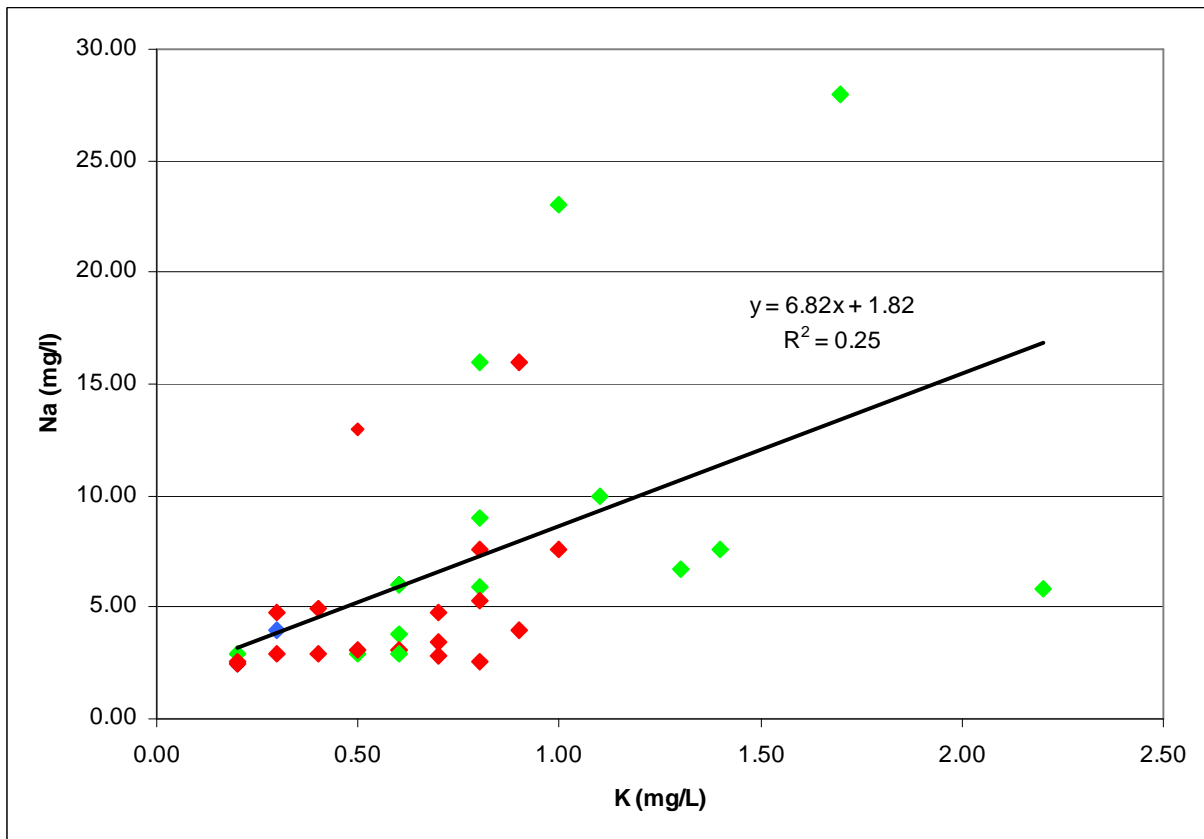


Figure 4.6: Potassium versus sodium. Red data points are surface water sites and green data points are North Bank groundwater sites. The two blue data points are Wairau River samples.

A weak positive covariance was found ($R^2 = 0.25$, Figure 4.6) between potassium and sodium. This weak correlation may be due to the minor amounts of both potassium and sodium present in the ground and surface waters of the North Bank while a stronger correlation may exist elsewhere for waters that are less dilute.

4.6 MAJOR ANIONS

4.6.1 Bicarbonate (Alkalinity)

Most alkalinity in groundwater is due to the amount of inorganic carbon ions present in solution, and therefore provides a measurement of bicarbonate or carbonate in solution (Deutsch, 1997). Bicarbonate is the main contributor to alkalinity for waters with a pH between 4.5 and 8.3, such as those encountered on the North Bank, with minor contribution possible from carbonate. The main sources of bicarbonate and carbonate are from reactions with water and CO_2 in the atmosphere, from sulphate reduction, and from dissolution of carbonate rocks (calcite, aragonite, and dolomite). If dissolution of calcite controls the chemistry of groundwater, then Ca and HCO_3 will fall on a 1:1 regression line (on a

milliequivalent basis). Most wells monitored as part of New Zealand's Groundwater Monitoring Programme have a greater proportion of HCO_3 compared to Ca (Rosen, 2001), as was the case for the North Bank study area (Figure 4.7). This suggests that HCO_3 is derived more from reactions involving soil organic matter than from calcite dissolution (Rosen, 2001).

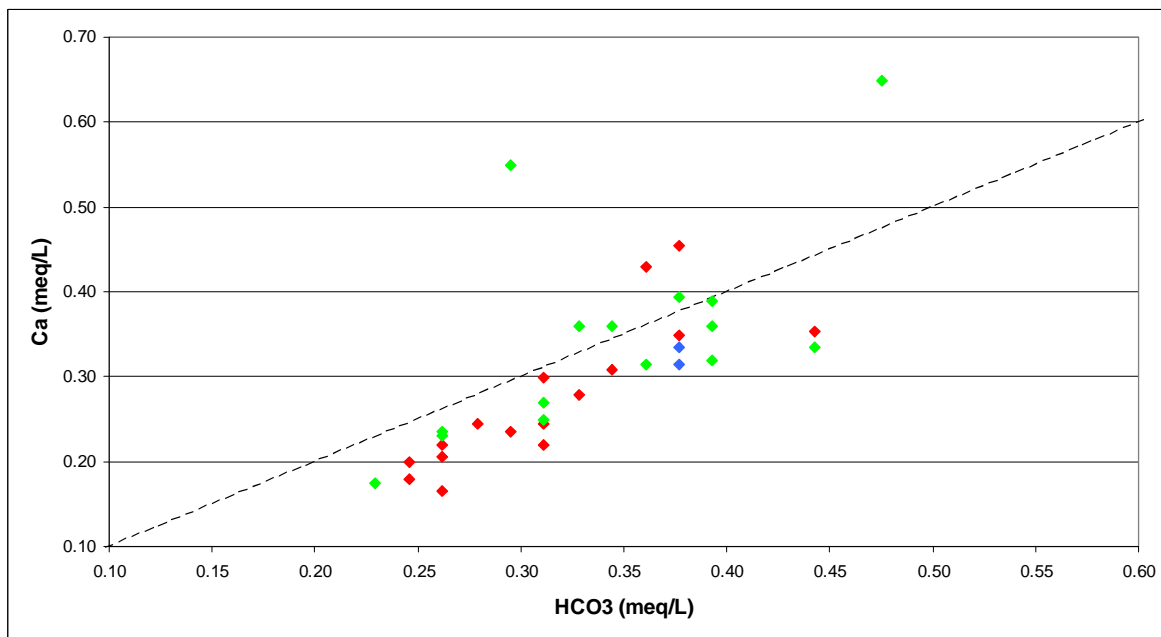


Figure 4.7: Bicarbonate in relation to Calcium. Red data points are surface water sites and green data points are groundwater sites. The two blue data points are Wairau River samples. Calcium carbonate-dominated aquifers tend to plot along the 1:1 line (dashed), while sample sites on the North Bank tend to have a greater proportion of HCO_3 than Calcium. The two groundwater samples that plot high above 1:1 line came from two vineyard sites.

Bicarbonate concentration ranged from 15 mg/L to 29 mg/L and was the dominant anion for all waters encountered on the North Bank. The average bicarbonate concentration was 20.3 mg/L for the North Bank while Close (2008) reports an average bicarbonate concentration of 35 mg/L for the unconfined Wairau Aquifer which attests to the dilute nature of the North Bank waters.

4.6.2 Sulphate

Natural sources of sulphate are mainly oxidation of pyrite, dissolution of sulphate minerals (gypsum and anhydrite) and from rain-water SO_4 which is principally sea-water derived (Rosen, 2001; Robinson and Botrell, 1997). In the North Bank setting, sea spray and rainwater are the most likely natural causes of sulphates present. The metamorphic nature of rock basement and alluvial derivatives means the rate of weathering is slow with minor mineral release through the oxidation of detrital pyrite and dissolution of sulphate minerals (Cunliffe, 1988; Hem, 1992; Robinson and Botrell, 1997).

Sulphate ranged from 1.2 mg/L to 6.6 mg/L for the study area (only one sample was over 3.8 mg/L). Rosen (2001) notes that increased sulphate concentrations can occur where fertiliser (gypsum) has been applied which may explain the relatively high value of 6.6 mg/l, found at one of two vineyard sites (P28w/4752), and which also had the highest TDS value. The mean sulphate concentration was 2.3 mg/L for the North Bank while mean sulphate concentrations for the unconfined Wairau Aquifer and Southern Valleys aquifers are slightly higher at 3.8 mg/L and 5.8 mg/L respectively (Close, 2008). This low mean reflects the dilute nature of the North Bank waters.

Magnesium versus sulphate concentration can be seen compared to the Seawater Concentration-Dilution Line (SCDL) in Figure 4.8. The SCDL represents the proportion of sulphate to magnesium expected in water evaporated from the ocean. Sample points which plot above the SCDL indicate significant land use inputs of sulphate (Rosen, 2001) while sample points which plot below can be due to relative enrichment of magnesium or, in reduced conditions, loss of sulphate. The majority of samples plot below the SCDL, and, as no reduced conditions were encountered, relative enrichment of magnesium can be inferred to be taking place rather than loss of sulphate. Interesting to note, Robinson and Botrell (1997) state that Caples Terrane schist (upon which the majority of the North Bank sits) yields less sulphate minerals through chemical dissolution than Torlesse greywacke which could be a factor in the relatively low sulphate levels for the North Bank.

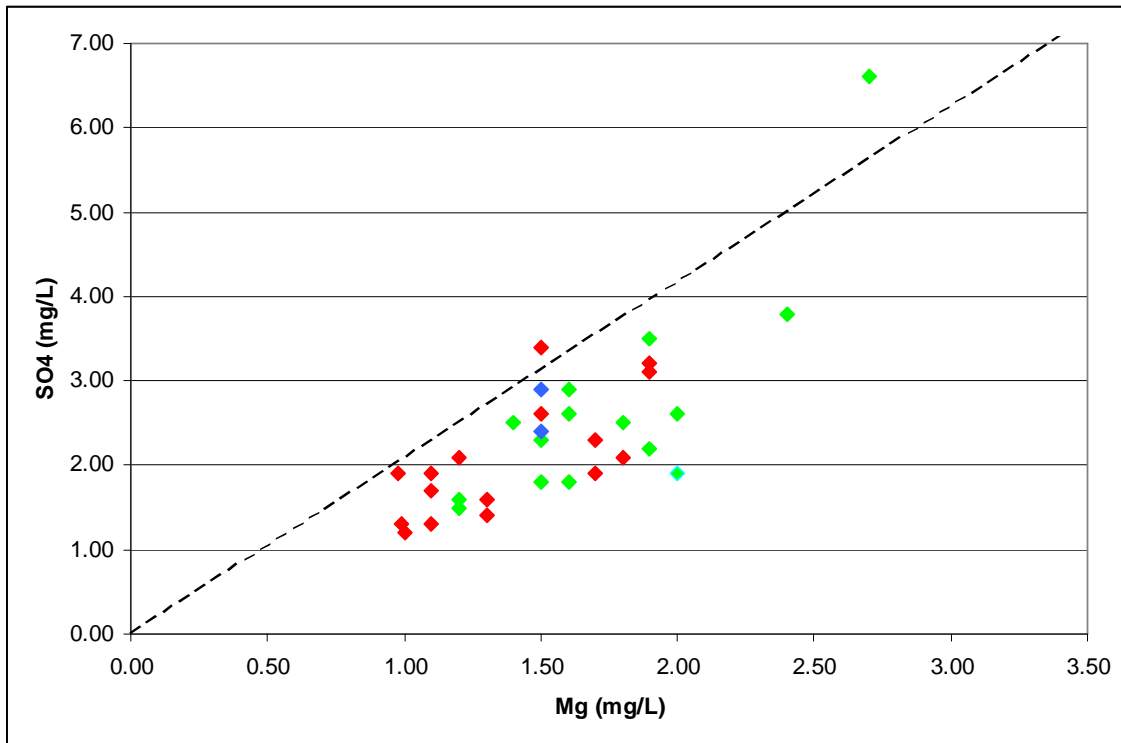


Figure 4.8: Magnesium versus sulphate. Red data points are surface water sites and green data points are groundwater sites. The two blue data points are Wairau River samples. The dashed line is the Seawater Concentration-Dilution Line.

4.6.3 Chloride

Similar to sulphate, sea spray can be assumed to be the main source of chloride when samples fall on the SCDL for sodium and chloride. Water evaporated from the ocean will contain dissolved sodium and chloride that are in the same ratio as in the ocean. Ground and surface waters collected closer to the ocean will have Na:Cl ratios similar to seawater and will fall on the SCDL. Thus, it can be determined which waters receive most of their sodium and chloride from the ocean and those that experience chloride enrichment due to water-rock interactions or other inputs. Nearly all North Bank samples fall close to the SCDL in Figure 4.9 which indicates that these waters receive most of their sodium and chloride from an oceanic source, and which is expected of most groundwater in New Zealand (Rosen, 2001). This is confirmed with chloride concentrations encountered during a North Bank tributary sampling run on 23 February 1978 where the expected trend of decreasing chloride values as distance from the coast/mean catchment altitude increased (Rae, 1988).

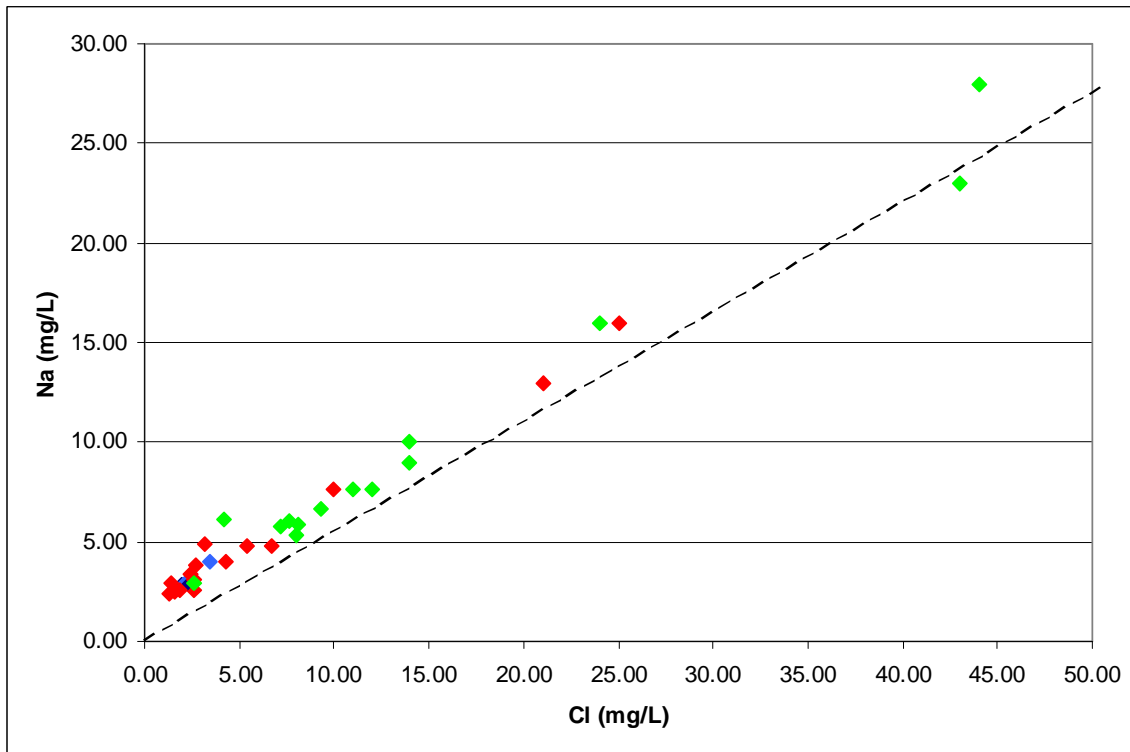


Figure 4.9: Chloride versus sodium. Red data points are surface water sites and green data points are groundwater sites. The two blue data points are Wairau River samples while the two significantly higher groundwater samples are vineyard sites. Dashed line is Seawater Concentration-Dilution Line

Chloride ranged from 1.3 mg/L to 25 mg/L with two much higher values of 43 mg/L and 44 mg/L found for two vineyard sites. Furthermore, any site that revealed a chloride concentration greater than 14 mg/L (of which there were eight) is currently used as pasture for stock (including the aforementioned vineyard sites). This suggests that soil chloride contents at these sites may be elevated due to chloride supply from animal effluent and/or potassium chloride fertilisers, in addition to any chloride naturally present in rainfall and groundwaters. It should be noted that at site 025 Terracedale Vineyard it was unclear if sample contamination occurred through sampling from a point at the well-head also used to apply dissolved fertiliser via irrigation (fertigation).

Twenty-seven sites contained less than 14 mg/L chloride, and despite instances of relatively elevated chloride, overall levels were low with no sample exceeding the aesthetic water quality guideline value of 250 mg/L. The mean chloride concentration of all data was 9 mg/L which compares to a mean of 4.2 mg/L for the unconfined Wairau aquifer (Close, 2008). When excluding samples that may be influenced by fertiliser application (inferred from Stiff plot characterisation, as discussed later), the mean chloride concentration dropped to 4.3 mg/L, in better agreement with the unconfined Wairau aquifer value.

4.7 TRACE METALS AND NON METALS

4.7.1 Iron and Manganese

Generally, iron and manganese will not be dissolved in solution when the groundwater dissolved oxygen content is high. Anoxic and reducing conditions are needed before appreciable levels of dissolved iron and manganese are detected. In New Zealand, iron is generally only detected in relatively slow moving groundwater where oxygen is consumed by reactions with organic matter or other chemicals (Rosen, 2001).

All samples had less than or equal to 0.02 mg/L of manganese present. All but two samples had less than 0.1 mg/L of iron present. The samples that did have detectable levels of iron present were P28w/4906 (0.53 mg/L), and 10100 (0.11 mg/L) and were an old disused well and a newly installed well respectively. Both likely contributed iron from oxidation of the well casings. North Bank water iron levels were generally very low with only the two aforementioned samples exceeding the aesthetic water quality guideline value for drinking water (0.2 mg/L - MoH, 2005), consistent with young oxidised water.

4.7.2 Boron

Boron is a major constituent of the mineral tourmaline and generally occurs in an unweathered state in sandstones (Hounslow, 1995). It is also present in seawater, and can be removed by adsorption onto clay minerals (Hounslow, 1995).

Ground and surface waters of the North Bank were found to contain only trace amounts of boron. Of all the samples analysed only two had levels of boron greater than 0.1 mg/L. These two samples were well 10100 in the Waikakaho Valley (0.15 mg/L) and P28w/3191 in the Langley-dale area (0.18 mg/L). Despite being the highest values gained as part of the sampling survey, the values are still well under the maximum allowable value for drinking water of 1.4 mg/L (MoH, 2005). All other sample concentrations were more dilute in respect to boron and ranged from less than 0.02 mg/L to 0.1 mg/L.

4.7.3 Fluoride

The presence of fluoride in New Zealand is generally quite low with most fresh water containing less than 1 mg/L (Hem, 1985) and most wells less than 0.5 mg/L (Rosen, 2001). Sources of fluoride include the dissolution of fluorite, apatite, fluoride-bearing micas and amphiboles or hydrothermal fluids (Rosen, 2001).

The maximum allowable value for fluoride in drinking water is 1.5 mg/L (MoH, 2005). No sample exceeded this amount with sample fluoride concentrations ranging from less than 0.05 mg/L to 0.1 mg/L. Given the very small concentrations of fluoride present, dissolution of fluorite, apatite, fluoride-bearing micas and amphiboles must not be occurring to any large degree upon the North Bank or the headwaters of the Wairau River.

4.7.4 Reactive Silica

Silica is a major constituent of most sandstones (and those since metamorphosed) and so, for the North Bank, natural sources of silica are through the weathering of the geological units present. At lower water temperatures silica is primarily derived from silicate weathering (Hounslow, 1995). As mentioned previously, silicate minerals produced through metamorphism have a slow rate of weathering and therefore little silica is available silica for solution. This is reflected in the hydrogeochemistry of the North Bank with low silica concentrations ranging from 7 mg/L to 15 mg/L, with an average of 9.7 mg/L. Rosen (2001) suggests that at concentrations <30 mg/L of both silica and sodium a correlation can be seen. Any correlation between silica and sodium levels at lower concentrations is likely due to equilibrium dissolution of sodium feldspars and ion exchange reactions within the aquifers (Rosen, 2001). In this study, a very weak correlation was found for the North Bank ($R^2 = 0.05$) where silica increases with increasing sodium levels.

4.7.5 Arsenic

Dissolved arsenic naturally present in groundwater is a result of the interaction between groundwater and aquifer sediments. The transition from solid phase arsenic to dissolved arsenic depends on several processes such as ion exchange and adsorption onto mineral surfaces, oxidation-reduction state of groundwater, formation of organic ligands, and pH (Rosen, 2001). Because most heavy metals are readily adsorbed onto oxides and clays in soils, it is generally considered that heavy metals become immobilised in the soil zone and do

not contribute greatly to groundwater contamination. However, preferential flow paths in an aquifer may allow greater transport of arsenic.

Arsenic concentrations were non-detectable except for two samples equal to 0.001 mg/L or greater. These were 0.001 mg/L at well P28w/4906 and 0.009 mg/L at Timms Creek at Cat Creek Road (TMC-1). Well P28w/4907, where there was no detectable arsenic and located 40 metres from well P28w/4906, shows that the slightly elevated arsenic levels at the latter are limited in extent. P28w/4906 is an old disused two-inch well 2.35 metres deep while P28w/4907 is 100mm in diameter and 7.9 metres deep, both tapping an unconfined water table type aquifer. A possible reason for the detection of arsenic at the two-inch well is that it has fallen into disuse and microbial dissolution of iron oxides in the well casing and sediment and, thus, the release of the arsenic has occurred over time. As reduced conditions within such an aquifer leading to arsenic solubility are unlikely to exist, well disuse is again the most likely explanation. Downstream of TMC-1, arsenic levels returned to less than 0.001 mg/L at Timms Creek at North Bank Road (TMC-2). This suggests that arsenic present at TMC-1 was localised in extent and diluted downstream by tributary inflow from Cat Creek.

The maximum acceptable value for drinking water is 0.01 mg/L which was exceeded by only two samples (P28w/4906 and TMC-1), neither of which are used for drinking water.

4.7.6 Nitrogen

Nitrogen is present in groundwater in several forms, and for this study both nitrate-nitrogen (NO_3^- -N) and ammonium-nitrogen (NH_4 -N) have been measured. In groundwater where oxygen is abundant, nitrate nitrogen is the stable form, whereas in oxygen depleted groundwater, ammonium nitrogen is the stable form. In New Zealand, the source of nitrogen is predominantly from anthropogenic sources such as fertilisers, grazing animals, sewage disposal, mineralisation due to tillage, landfills and horticulture (Close *et al.*, 2001). Natural sources of nitrogen include rain, igneous rocks, dissolution of nitrate minerals, while deep geothermal fluids are rare. Nitrogen from untreated human waste water is either in the form of ammonium or organic nitrogen, while chemical fertilisers contribute ammonium or nitrate nitrogen (Close, *et al.*, 2001). Concentrations of nitrate are expected to be highest in the youngest groundwaters.

All samples tested from the North Bank were low in ammonium-nitrogen (<0.005 mg/L except for five samples which all had less than 0.028 mg/L). This is consistent with oxygen-rich water where ammonium-nitrogen is not the stable form. The maximum acceptable value for ammonium-nitrogen for drinking water is 0.2 mg/L (MoH, 2005) and was not exceeded by any sample. Concentration of nitrate-nitrogen upon the North Bank ranged from <0.03 mg/L to 2.1 and did not exceed the maximum allowable value for nitrate-nitrogen for drinking water of 11.3 mg/L (MoH, 2005). There was no discernable spatial pattern to nitrate levels except that elevated nitrate levels generally coincided with pastoral sites.

4.8 WATER QUALITY

4.8.1 pH

Potential Hydrogen (pH) refers to the amount of activity of free, uncomplexed hydrogen ions found in a solution. The amount of free hydrogen ions present determines the acidity or alkalinity of the solution as hydrogen ions participate in most of the chemical reactions that affect water composition (Driscoll, 1986; Deutsch, 1997).

The pH of all the waters sampled ranged from 6.1 to 7.8 in the field and 6.2 to 7.7 with laboratory analysis. Laboratory-determined pH was consistent with field-measured values, although field values were often more acidic by ≤ 0.2 . This difference is likely due to the pH change, specifically through adjustment of carbonate-bicarbonate equilibria, in the period between sampling and analysis. Mean groundwater pH was less than both mean surface water pH and mean Wairau River pH (Table 4.4).

Table 4.4: Mean field and laboratory pH values

Water type/source	Mean Field pH	Mean Laboratory pH
Groundwater	6.6	6.8
Surface water	7.0	7.0
Wairau River water	7.7	7.7

The Wairau River samples, being slightly alkaline, were characteristic of both this river and New Zealand rivers in general. Robinson and Botrell (1997) measured 7.11 to 7.99 for the Wairau River and Close and Davies-Colley (1990) report a pH range of 7.0 to 8.5 for New Zealand rivers unaffected by volcanic or geothermal activity. The slightly greater acidity displayed by North Bank groundwater compared to North Bank surface water and the Wairau River may be a function of groundwater residence time and degree of exposure to the atmosphere. As water seeps below the surface, it passes through the soil where microbial respiration processes release CO₂ which lowers the pH of water (Freeze and Cherry, 1977). Longer groundwater residence times can also promote lower pH through greater water-rock interaction and addition of minerals to groundwater that lower pH. The net result of both processes can be an altered pH from that of rain and surface water and can perhaps explain the lowered pH of North Bank groundwater.

Overall, these waters can be described as neutral after Hounslow (1995), where pH is equal to 6.5 - 7.8. The aesthetic guideline value for drinking water recommends that pH should be within the range 7.0 to 8.5 (MoH, 2005) which nineteen samples exceeded. However, these samples were only mildly acidic (6.2 to 6.9) and are unlikely to induce plumbosolvency or health concerns.

From the limited number of wells sampled, no correlation appeared to exist between pH and well depth.

4.8.2 Total Hardness

Water hardness is primarily determined by calcium and magnesium cations, although other dissolved compounds such as bicarbonates and sulphates can contribute in some circumstances (Driscoll, 1986). Hard water contains more minerals than soft water and is more difficult to produce a soap lather with. Calcium usually enters the water as calcium carbonate (CaCO₃) and for this reason water hardness is the sum of calcium plus magnesium expressed as calcium carbonate.

All North Bank samples were found to be soft water with calcium carbonate concentration ranging from 14 mg/L to 27 mg/L. The aesthetic guideline value for drinking water is <200 mg/L which no samples exceeded.

4.8.3 Electrical Conductivity

The electrical conductivity of water is its ability to conduct an electrical current (Driscoll, 1986). As it is the dissolved ions in water that conduct electricity, generally the higher the electrical conductivity (EC), the higher the ion concentration and consequently TDS. However, not all minerals conduct electricity in the same way with sodium chloride for instance having a higher conductance than calcium bicarbonate (Driscoll, 1986). Therefore, the correlation between EC and TDS for waters predominated by sodium chloride is approximately 0.5 mg/L TDS per $\mu\text{S}/\text{cm}$ EC while a mineral composition including bicarbonates would have a conversion of 0.6 – 0.7 mg/L TDS per $\mu\text{S}/\text{cm}$ EC (Weast, 1978). This study found a conversion of 0.66 mg/L TDS per $\mu\text{S}/\text{cm}$ EC with a strong positive correlation ($R^2 = 0.99$, Figure 4.10). The average EC for groundwater was 100.3 $\mu\text{S}/\text{cm}$ while the average EC for surface water was 65.0 $\mu\text{S}/\text{cm}$ which is a reflection of both longer residence time and further water-rock interaction of groundwater compared to surface water.

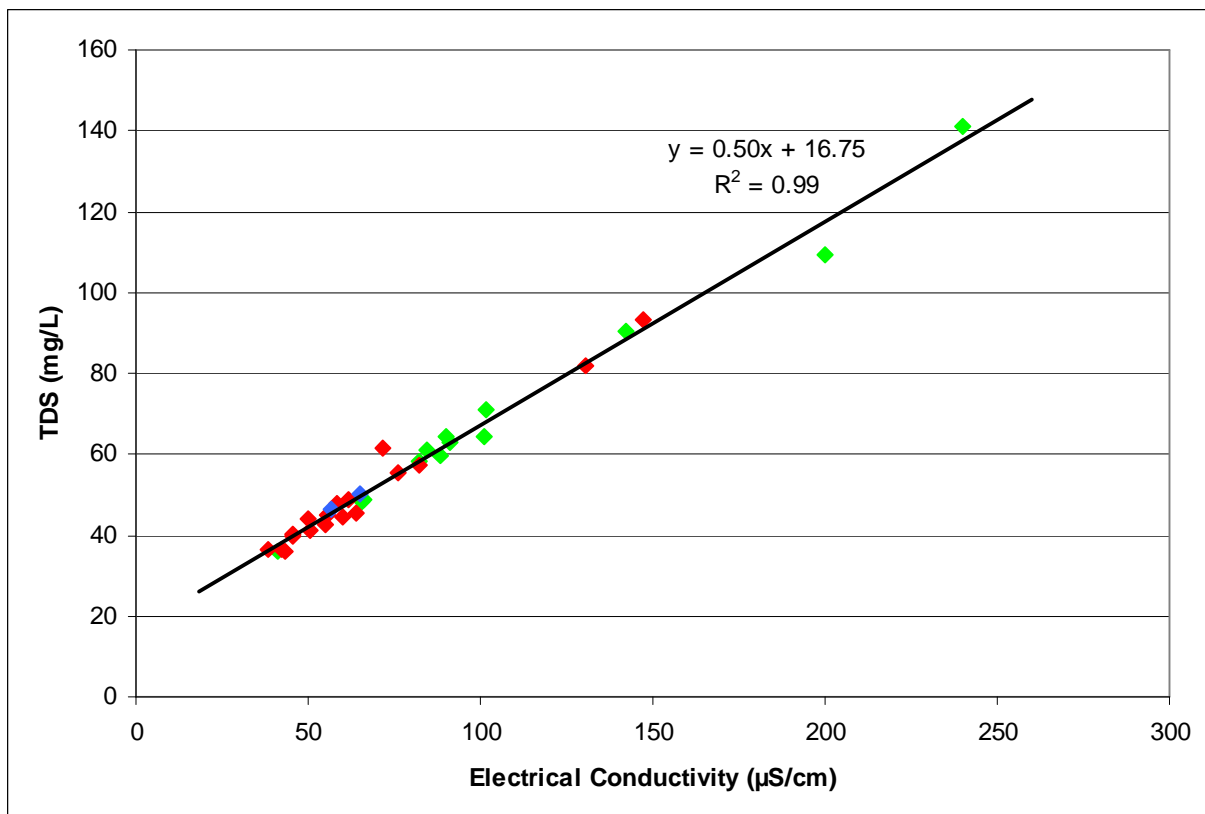


Figure 4.10: Total Dissolved Solids (TDS) versus Electrical Conductivity (EC). Red data points are surface water sites and green data points are groundwater sites. The two blue data points are Wairau River samples. A linear relationship is known to exist where EC is proportional to TDS (Weast, 1978), as was the case for the North Bank.

4.8.4 Dissolved Oxygen

Dissolved oxygen (DO) is the molecular oxygen dissolved in water and is used as an indicator of the biochemical conditions of ground and surface water. Oxygen is sourced mainly from the atmosphere, as well as photosynthesis of aquatic plants, and is significant for chemical and biological reactions. Pressure and temperature are the main controls on DO content as cold water at high atmospheric pressure holds more dissolved oxygen than warm water at low atmospheric pressure (Driscoll, 1986). Other factors that influence DO include the volume and velocity of water, altitude, TDS, and season. DO levels should be highest in water close to the surface and close to recharge areas. As water travels through an aquifer from the recharge point to the discharge point, oxygen is consumed by any organic matter present and/or mineral interactions (Hounslow, 1995). This process of oxygen consumption can result in anoxic groundwater and a reducing environment where other elements may form.

DO levels ranged from 6.03 mg/L to 12.39 mg/L with the highest DO levels encountered in flowing surface waters, particularly the Wairau River. The average DO level for surface water was 10.9 mg/L and the average DO level for groundwater was 8.3 mg/L. This is most likely a function of the greater exposure to the atmosphere surface water would be expected to have compared to groundwater, along with greater volume and velocity of water. This was similarly reflected in percent saturation of DO with an average of 75 percent for groundwater and 94 percent for surface water (1 d.p.). Dissolved oxygen values measured in the course of the sampling survey are consistent with a young oxidised water resource.

4.8.5 Coliforms and *Escherichia coli*

Coliform bacteria are commonly used as indicator organisms and while some coliforms can be present in unpolluted water, most faecal coliforms are of faecal origin (Sinton, 2001). One such species is *Escherichia coli* (*E. coli*), a bacterium that indicates the presence of faecal material and, therefore, the potential presence of pathogenic organisms. Both faecal coliforms and *E. coli* were tested for in this study, detection of which indicated contamination from human or animal waste.

The maximum acceptable value for drinking water is <1 *E. coli* in 100 mL of sample. Two wells exceeded this value (P Day and Wadsworth Shearing Shed well), both having one *E. coli* in 100 mL of sample. These two wells are located in pastoral settings with contamination from sheep or other stock possible. Numerous surface water samples also exceeded this

value; these were both samples from the Wairau River and then west to east respectively; Burnt Scrub Creek, Bown Reservoir, Timms Creek at Cat Creek Rd and North Bank Rd, Pine Stream Valley, Wadsworth Spring, Bartlett's Creek, Swamp Gully Stream, Coatbridge Stream (Deer Park Stream), Terrace Spring, Onamalutu River at the Onamalutu Domain and North Bank Rd, and the Waikakaho River at Rocky Creek, MDC monitoring well site and Tuamarina Track Rd. Stock animals have access to nearly all of these sites or have access to the water upstream. While water from these sites do not meet New Zealand Drinking Water Standards, few if any sites would be used for that purpose.

4.9 GROUNDWATER CLASSIFICATION

4.9.1 Piper trilinear diagram

A Piper plot has the ability to display variation in water chemistry over the whole study area on a single graph so that major groupings of hydrochemical facies can be recognised visually (Freeze & Cherry, 1979). Hydrochemical facies are classes of water types with distinct chemical compositions. The specific hydrochemical facies are defined by the major cations and anions present on an equivalent basis with the apex of each triangle representing 100 percent of a given ion in milli-equivalents. The data point is plotted within each triangle according to the respective percentage of cations (left triangle) and anions (right triangle) the sample contains, and then projected upwards into the diamond. Where the two lines of extrapolation meet within the diamond gives the water type. The single most common water type in New Zealand is a Ca-Na-HCO₃ solution followed closely by Ca-HCO₃ (Rosen, 2001). There are many types of classification that can be used for defining hydrochemical facies with the specific classes adopted depending on the environment in question (Freeze and Cherry, 1979). The dominance of calcium, sodium and bicarbonate in the Wairau Valley will necessitate the reliance on minor constituents to differentiate sub-groups.

Data gathered by this study are presented in Figure 4.11. Most waters plot in the Ca-Na-K-HCO₃ type facies, with water samples tracking toward the right as Na and K content increases. This then leads to waters that fall into the Ca-Na-K-HCO₃ facies and eventually Na-K-HCO₃-Cl facies. These latter groups of Ca-Na-K-HCO₃ and Na-K-HCO₃-Cl waters were found principally within the Waikakaho Valley and Coatbridge/Langleydale area respectively, and instances of both within the Bartlett's Creek area.

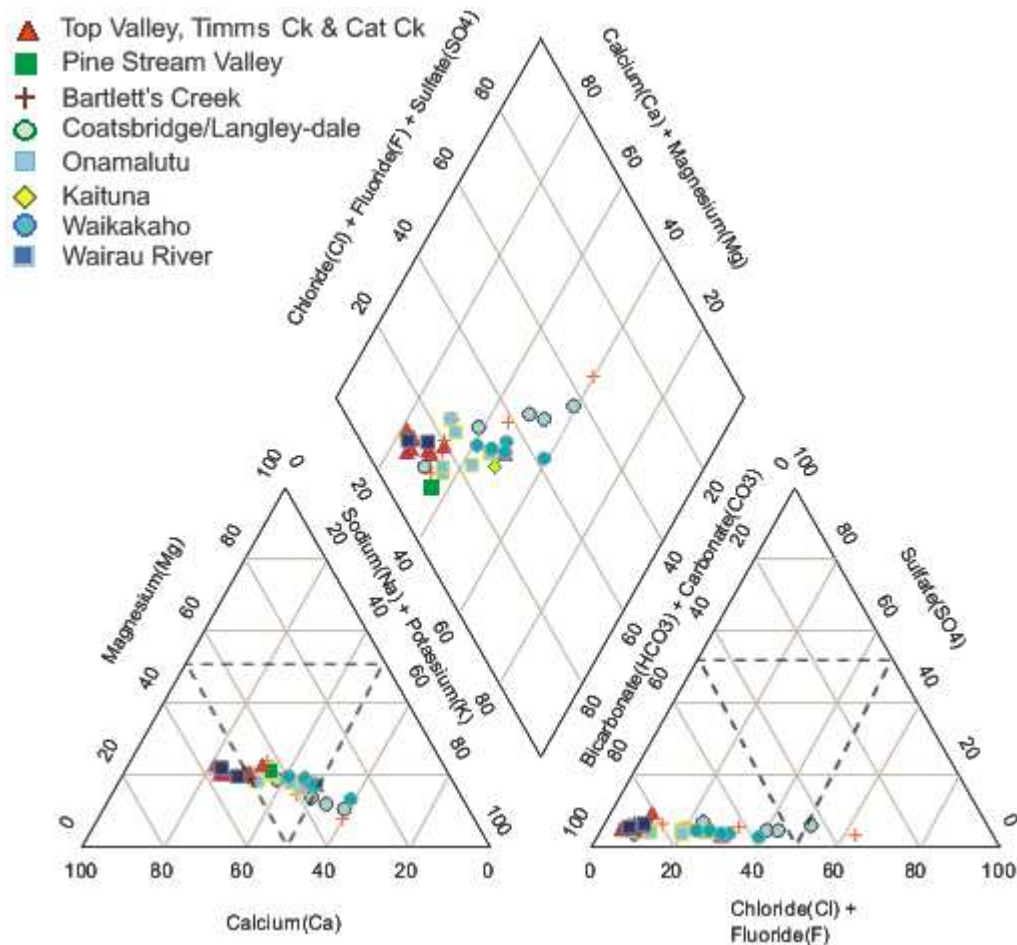


Figure 4.11: Piper trilinear plot displaying the major ionic species collected for this study. Most waters plot as Ca-Na-K-HCO₃ type and as they track to the right, fall closer to Na-K-HCO₃-Cl type waters

The finding from this study of Ca-Na-K-HCO₃ as the predominant water type for the North Bank is in agreement with previous study within the Kaituna Valley where Ca-Na-K-HCO₃ type waters were also prevalent (Taylor, 2004). Rae (1988) and Close (1999), report an average water type composition of Ca-HCO₃ for the Wairau Valley at large, and illustrates the consistent dominance of calcium and bicarbonate ions within the Marlborough setting. Groundwater classification within the unconfined Wairau Aquifer has been further refined and characterised as Ca-Na-Mg-HCO₃ (Wilson, 2008; Daughney and Reeves, 2003) and provides a point of differentiation from North Bank waters. The slightly higher concentration of Mg in Wairau Aquifer waters is a reflection of the longer residence time and more evolved nature of water.

Groundwaters tested and that fell into the Na-Cl-HCO₃-Cl facies, such as those from Waikakaho Valley, confirms past work carried out there where Na-Ca-HCO₃-Cl type water was present (MDC, 2008). The higher concentrations of sodium and chloride sometimes

encountered in the Waikakaho Valley, Coatbridge/Langley-dale area, and Bartlett's Creek compared to the rest of the North Bank can be attributed to the farming practices in those areas. Sites currently used for viticulture produced the most chloride-abundant Na-K-HCO₃-Cl type waters while sites used for pastoral farming produced slightly less chloride-abundant waters (Ca-Na-K-HCO₃). Any progression from Ca-Na-K-HCO₃ type waters to Na-K-HCO₃-Cl type waters in a given area is attributed solely to land use practices rather than from mixing of North Bank tributary water with Wairau River water. Both the Bartlett's Creek and Coatbridge/Langley-dale areas demonstrated a progression from Ca-Na-K-HCO₃ type waters to Na-K-HCO₃-Cl type waters, however, water samples which are expected to receive their recharge principally from North Bank tributaries or, conversely, the Wairau River, shared a common chemical signature (Ca-Na-K-HCO₃). While this does not rule out that mixing occurs (which in fact it does as demonstrated by oxygen isotope signatures, Chapter 5), the chemical signature of North Bank tributaries and the Wairau River are too similar to distinguish by Piper plot, and land use practices are the controlling factor in any shift in chemical signature.

The ground and surface water upon the North Bank was found to be sufficiently dilute in terms of TDS that common farming practices which add relatively minor amounts of salts to the soil are able to be registered. This is further examined through the various Stiff plots produced from the area.

4.9.2 Stiff plots

Stiff plots are a simple method to display groundwater chemistry data in order to gain a pictorial representation of chemistry patterns. By comparing the irregular shapes they form, relationships between groundwater samples can be identified. Stiff plots use the milli-equivalent values of the major anions and major cations which are plotted to the right and left of a vertical axis respectively. The size of the shape is proportional to the total ion concentration while the distance from the vertical axis represents the prevalence of a given ion. The pairs used in this study for the Stiff plots are Na + K and Cl, Ca and HCO₃, and Mg and SO₄.

Representative Stiff plots are shown in Figure 4.12 for the Wairau River and each tributary valley. A distinctive elongate hexagonal shape is produced from nearly all valleys and the Wairau River indicating the dominance of Calcium and Bicarbonate ions within the water.

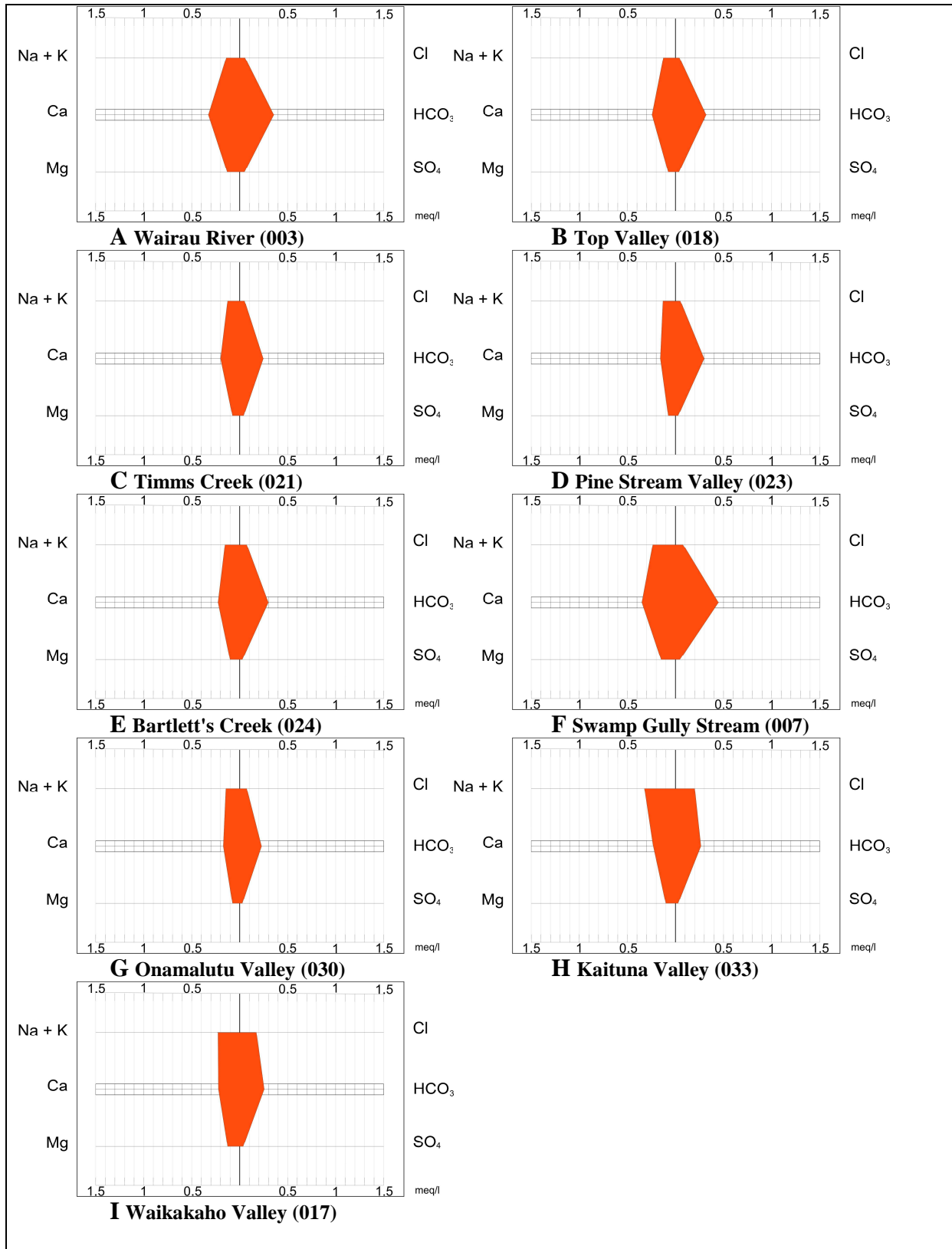


Figure 4.12: Representative Stiff plots from across the Study area. Plots are shown for the Wairau River and then, west to east respectively, Top Valley, Timms Creek, Pine Stream Valley, Bartlett's Creek, Swamp Gully Stream, Onamalutu Valley, Kaituna Valley and Waikakaho Valley. The Kaituna Valley sample may receive recharge from the Onamalutu Valley due to its proximity, along with elevated Na + K from vineyard.

Stiff plots for all sample sites are plotted spatially in Figure 4.13. This shows the hydrochemical pattern formed by the waters across the area in order to visually see any correlation or changes present. The elongate hexagonal shape is preserved across the majority of the study area with localised instances of greater sodium plus potassium, and chloride causing a fan shaped Stiff plot to develop. These are sites (from west to east respectively) 025, 027, 004, 005, 006, 009, 016, 035, 034, 014 and 015. These sites are areas of farming and/or viticulture which would be consistent with a possible influence from fertilisation application. As the area of each Stiff plot is proportional to the TDS present, sites with greater sodium and potassium, and chloride also have a larger coloured area on their corresponding Stiff plot.

A point of reiteration is that the dilute ground and surface waters of the North Bank show a marked contrast between calcium-bicarbonate type waters (elongate hexagon-shaped Stiff plot) and sodium-chloride type waters (fan-shaped Stiff plot) despite their relatively low TDS contents. This can be used to infer where fertiliser application has had an impact upon the hydrochemical signature of the North bank waters. In regard to the use of Stiff plots to differentiate between water sourced from North Bank tributaries versus the Wairau River, water chemistry was found to be too similar to differentiate between the two. Both sources of water produce elongate hexagonal shaped Stiff plots that do not vary significantly enough in chemical signature due to the dilute nature of both water sources.

Worth noting is that the groundwater sample from Kaituna Valley (033) may not necessarily be representative of that valley due to its proximity to the Onamalutu River from which it might be expected to receive recharge. However, examination of the mean chemical values reported for Kaituna groundwater by Close (2008) reveals that Kaituna water composition would not be expected to be greatly different from that displayed in Figure 4.12 (H).

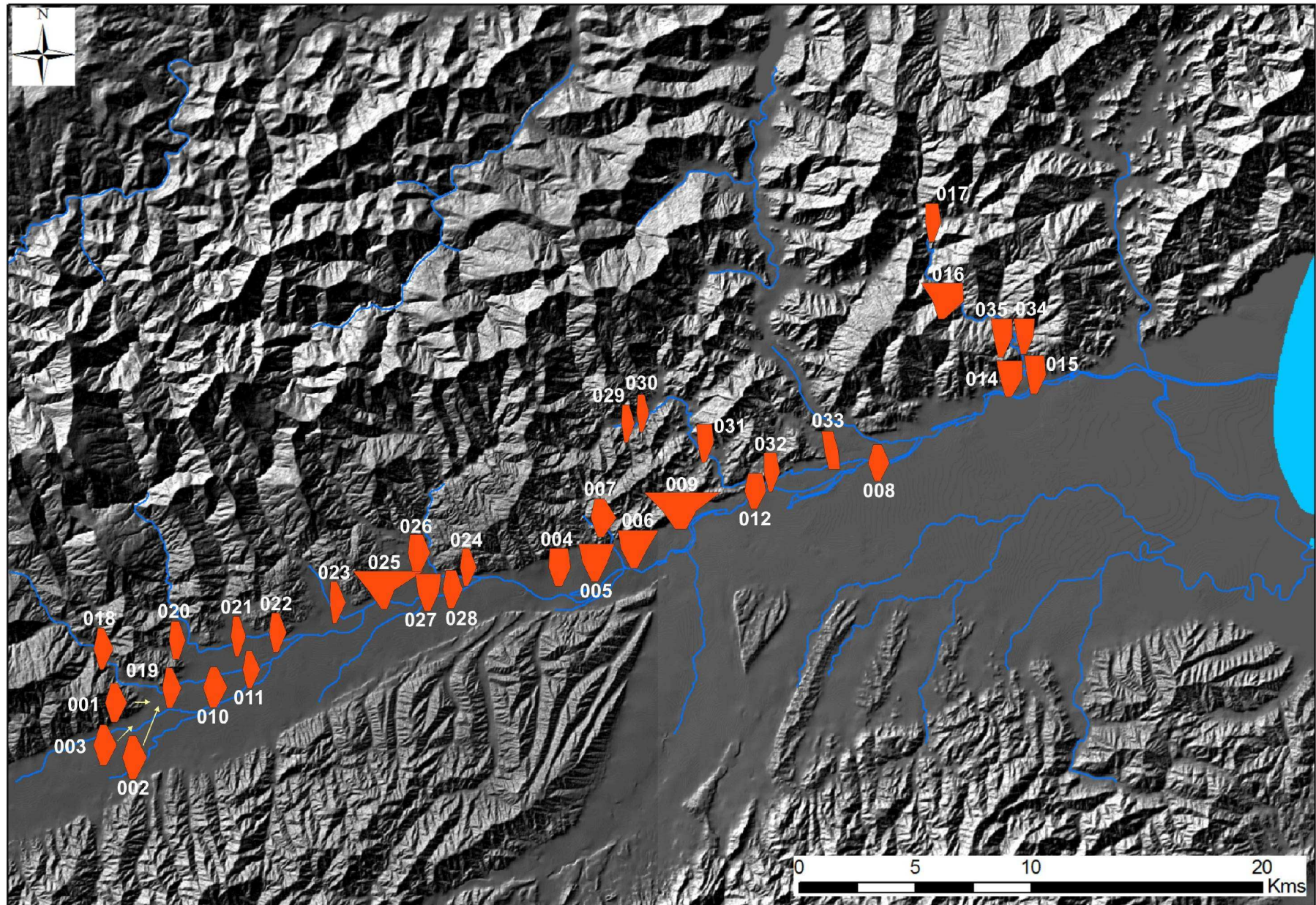


Figure 4.13: Stiff plots plotted spatially across the study area

Catchment size was examined in relation to the average TDS value gained for each valley to see what correlation might exist (Table 4.5). A very weak negative correlation was found ($R^2 = 0.04$) where the larger the catchment size, the smaller the average TDS content. While a positive correlation would be more typical in a hydrogeochemical investigation (the larger the catchment area, the greater the TDS content of groundwater) the reverse may be possible in the North Bank setting. Metamorphic lithology with a limited ability to reduce minerals to groundwater, in conjunction with a relatively high volume of water with a short residence time, may result in dilution of any soluble minerals present.

Table 4.5: Catchment size and the average TDS value found therein. A weak correlation was found between catchment size and average TDS ($R^2 = 0.04$).

Catchment	Catchment Size (m²)	Average TDS (mg/l)
Top Valley	87, 902	51.3
Timms Creek	49, 829	48.5
Cat Creek	18, 815	-
Burnt Scrub Creek	6,945	58.2
Pine Valley	36, 220	46
Fabian's Valley	22, 929	
Bartlett's Creek	53, 594	
<i>Fabian's & Bartlett's Total</i>	76, 523	66.9
Swamp Gully	8, 591	78
Onamalutu Valley	69, 074	58.1
Kaituna Valley	37, 762	58.2
Waikakaho Valley	57, 201	75.3
Pukaka Drain	23, 918	-

4.10 CHAPTER SUMMARY

A slight ion imbalance was recognised in all water samples tested. This is attributed to the dilute nature of the waters encountered and the difficulty in achieving ionic balance in dilute waters due to the magnification of analytical errors in dilute waters (Fritz, 1994). An ion imbalance was found by the 2008 study by the MDC within the Waikakaho Valley where again, dilute waters were encountered.

Additionally, alkalinity was laboratory-analysed only and not in the field which could introduce a further source of error through a portion of bicarbonate re-equilibrating to sample bottle conditions before analyses were carried out.

Calcium was the dominant cation and bicarbonate was the dominant anion. The water chemistry of the study area indicates a high quality groundwater resource that is relatively young as it has not progressed through the Chebotarev sequence. Low rates of chemical weathering, in conjunction with high rates of through-flow driven by relatively high rainfall amounts in the higher altitude catchment area, results in groundwater of low ionic load.

Sulphate and chloride ions present in ground and surface water were inferred to come from sea spray, incorporated in rainfall, as these determinands fell close to the seawater dissolution-concentration line. Most chemical constituents were low in concentration with rare elevated concentrations of sodium, potassium and chloride presumably derived from fertiliser application. Dissolved oxygen content was high for the majority of waters encountered which attests to the oxygen-rich nature of the groundwater environment. Whilst the North Bank lithology is not conducive to great amounts of iron and arsenic solubility, these constituents were also low in concentration as a result of the highly aerobic environment.

The groundwater upon the North Bank and tributary valleys is predominantly Ca-Na-K-HCO₃ type water from Piper trilinear plot. This corresponds well to previous study on the North Bank with subtle variations present over the study area. These hydrochemical variations are likely due to anthropogenic causes such as farming and viticulture.

Stiff plots were found to be an effective tool in identifying possible sites of hydrogeochemical influence from fertiliser use. The majority of waters on the North Bank formed an elongate hexagon-shaped Stiff plot due to the calcium-bicarbonate type waters, while several instances of sodium-chloride type fan-shaped Stiff plots were found at farming and viticultural sites. As these sites are likely to use fertiliser, fertiliser use is suggested as the most likely cause of elevated levels of sodium, potassium and chloride. Phosphate analyses would be beneficial to confirm this theory. Stiff plots, however, proved unable to differentiate between waters sourced from tributary valleys versus the Wairau River, likely due to the dilute and similar chemical nature of both.

Chapter 5

STABLE ISOTOPES

5.1 INTRODUCTION

Stable isotopes can help to determine the source and transport path of surface and groundwaters, and are particularly useful when used in conjunction with water chemistry. Relationships between the isotopic composition of meteoric-derived waters and altitude, temperature, latitude, and storm-track path facilitate the interpretation of water source regions where long-term precipitation isotope datasets are not available, as is the case throughout much of New Zealand. In an effort to document the isotopic composition of environmental water in the Wairau region, ground and surface waters were sampled for both oxygen and hydrogen isotopic analysis in August 2009. These data provide an opportunity to explore the potential use of stable isotopic composition as a forensic tool capable of distinguishing Wairau River water from North Bank tributary groundwater sources.

5.2 STABLE ISOTOPES BACKGROUND

Stable isotope analysis is commonly used in groundwater studies to determine the source of recharge, particularly when used in conjunction with hydrogeochemistry and hydrogeology. Stable isotopes of oxygen and hydrogen provide an important tracer of hydrological processes (Aggarwal et al., 2005; Stewart, 2008). In addition, they behave conservatively in groundwater systems and they have an ability to reveal evaporation and mixing influences when both hydrogen and oxygen isotopic compositions are determined (Taylor, 2003).

An isotope is an atom of a particular element that is defined by the number of neutrons and protons in its nucleus (Drever, 1997). Different isotopes of the same element, therefore, have different atomic masses. This difference in mass causes a fractionation in the distribution of the different isotopes during a number of natural processes, such as the cycling of water through the near surface environment. Stable isotopes are not radioactive. In contrast, a radioactive isotope has an unstable nucleus that decays, emitting alpha, beta, or gamma rays until a new stable state is reached.

The most commonly studied isotopes in hydrogeology are oxygen-16 (^{16}O), oxygen-18 (^{18}O), protium (^1H), and deuterium (^2H). The relative proportions of ^{18}O and ^2H in precipitation are modified by thermodynamic processes in the atmosphere and they can give an indication of the recharge source region.

The relative terrestrial abundance of the two most common isotopes of oxygen is 99.796 percent for ^{16}O and 0.204 percent for ^{18}O (Clark and Fritz, 1991). As the variation in the isotopically heavier element ^{18}O relative to lighter ^{16}O is often very small, stable isotope ratios are reported relative to a reference standard as delta (δ) values, in units of parts per thousand (‰) where:

$$\delta = \frac{R_{\text{sample}} - R_{\text{reference}}}{R_{\text{reference}}} \times 1000 \text{ ‰}$$

(Equation 5.1)

By convention, hydrogen and oxygen isotopic data, for water samples, are referenced to the *Vienna Standard Mean Ocean Water* (V-SMOW) scale. V-SMOW is considered to be representative of average ocean water and has both a $\delta^{18}\text{O}$ value and δD value of 0‰. Craig (1961) found that hydrogen and oxygen stable isotopes derived from precipitation from an oceanic source have a linear trend, expressed as $\delta\text{D} = 8 \times \delta^{18}\text{O} + 10$ at the global scale, and later refined to $\delta\text{D} = 8.13 \times \delta^{18}\text{O} + 10.8$ to form the Global Meteoric Water Line (GMWL, Figure 5.1). The GMWL represents a global average obtained from surface water sites though it has been subsequently found that localised variations (e.g. climate) will change the form of the equation thus producing local meteoric water lines (LMWL). The equation for the New Zealand LMWL is $\delta\text{D} = 8.13 \times \delta^{18}\text{O} + 13$ (Stewart & Taylor 1981). In this study, the GMWL will be referred to instead as it is a better fit with North Bank data and has also been used in previous groundwater studies in the Wairau Valley and Plains (i.e. Taylor et al., 1992). The GMWL also applies more closely to other easterly climatic zones such as Canterbury and Otago due to the effect of the Southern Alps 'wringing out' south-easterly or westerly air masses (Stewart and Morgenstern, 2001).

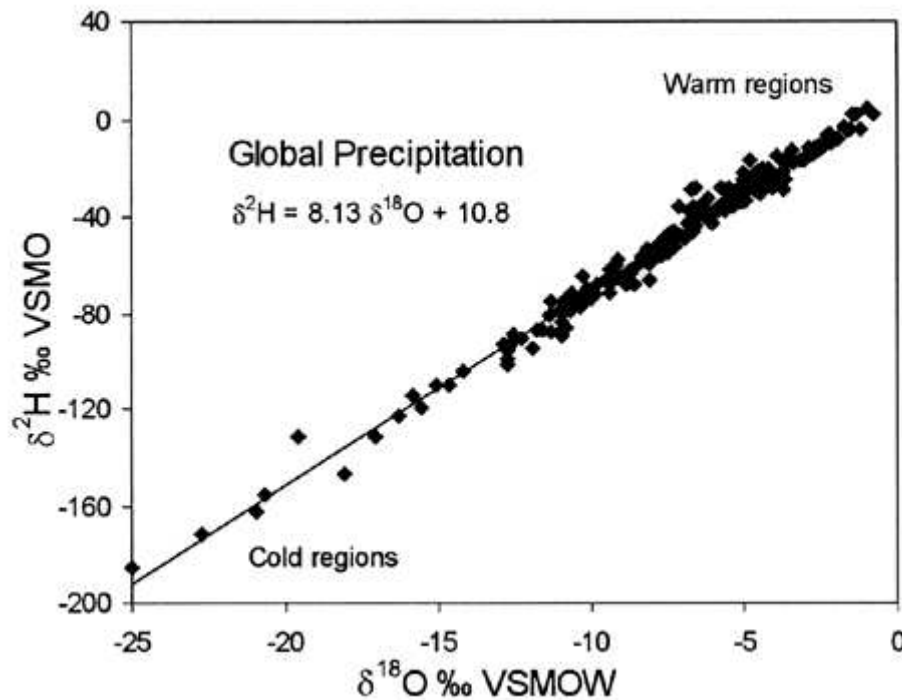


Figure 5.1: $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ with the GMWL displayed which follows the trend $\delta^2\text{H} = 8.13 \times \delta^{18}\text{O} + 10.8$. Cold regions can be seen to have more negative $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values which indicates the effect of temperature (Clark and Fritz, 1997)

Isotopic fractionation during hydrologic cycling enables tracing of groundwater sources. The relative atomic weights of the hydrogen and oxygen isotopes determine the molecular weight of a water molecule. Heavy water ($^2\text{H}_2\ ^{16}\text{O}$), has a mass of 20 compared to normal water ($^1\text{H}_2\ ^{16}\text{O}$), which has a mass of 18. The difference in mass of the water molecules creates differences in thermodynamic reaction rates which leads to the isotopic separation or *fractionation* described by Urey (1947). The difference in reaction rates will leave a residual fluid, such as the ocean, relatively 'enriched' in the heavy isotopes, while water vapour and precipitation is relatively 'depleted' in the heavy isotopes. On balance, this fractionation during evaporation has a negligible effect on the overall isotopic composition of the global oceans on short-time scales due to the immense volume of the ocean compared to atmospheric water vapour (Rosen, 2001). However, fractionation effects in the atmosphere are significant.

Water from different sources, which has been subjected to different thermodynamic and environmental conditions, can be distinguished by variations in isotopic ratios. The major isotopic fractionation effects relevant to water are described below. These effects are primarily the result of Rayleigh fractionation: isotopic fractionation in an open system in which a portion of water vapour condenses from a source reservoir (e.g. air parcel), preferentially removing isotopically 'heavy' water molecules from the remaining vapour phase.

5.2.1 The Temperature Effect

A major parameter that determines the isotopic values of precipitation is the temperature effect due to greater fractionation taking place at low temperatures than at high temperatures. The composition of precipitation depends on both the temperature at which oceanic water is evaporated into the air and, more significantly, the temperature of condensation at which clouds and precipitation are formed (Mazor, 1991). Through the process of Rayleigh fractionation, δD and $\delta^{18}O$ are predicted to become increasingly negative with lower ambient temperatures. The large variation of isotopic composition of groundwater is largely due to the temperature effect.

5.2.2 The Latitude Effect

The latitude effect stems from the temperature effect as colder temperatures are typically encountered further away from the equator. Figure 5.1 shows how precipitation in cold regions tends to be isotopically depleted compared to precipitation in warmer regions. This is a two-part process where the greatest evaporation occurs in regions with the highest surface ocean temperatures. The atmospheric vapour formed progressively condenses during transport to higher latitudes with lower temperatures reaching values as low as -57 ‰ in Antarctica.

5.2.3 The Altitude Effect

At higher altitudes where temperatures are colder, precipitation will be isotopically depleted. In New Zealand, ^{18}O depletion varies about -0.21 ‰ per 100m rise in altitude with a corresponding decrease of about -1.7‰ for 2H (Rosen, 2001). This effect is very useful in hydrogeological studies, as it distinguishes between groundwaters recharged at high altitudes and those closer to sea-level (Clark and Fritz, 1997)

5.2.4 The Continental Effect

Water becomes increasingly depleted in heavy isotopes with distance from the sea. After water has evaporated from the sea, and is in the atmosphere as water vapour, it moves inland and condenses, to fall as rain. This process results in rainfall that is isotopically enriched relative to the water vapour. However, as the vapour moves increasingly inland, there is a progressive depletion of heavy isotopes, resulting in heavy isotope depletion increasing with distance from the sea. Subsequent rainfall, although enriched relative to the water vapour from which it was created, is also progressively depleted with the distance from the sea. An illustration of this is given in Figure 5.2 where heavy isotopes in the atmosphere are said to

become "rained out" as precipitation moves inland with residual water vapour increasingly becoming isotopically lighter.

5.2.5 Amount Effect

The isotopic composition of precipitation can change during the course of a single rain event. It has been found that heavy rain events can result in more negative δD and $\delta^{18}O$ values. Similar to the continental effect, heavy isotopes are preferentially rained out first so that rainfall thereafter is progressively lighter in regard to isotopes of ^{18}O and D. This effect approximately yields a 1.5 ‰ depletion in the $\delta^{18}O$ of precipitation for every 100 mm increase in rainfall. Other contributions to this effect can be low ambient temperatures which form isotopically light clouds and low ambient temperatures which cause heavier rains. Falling rain may also undergo evaporation which enriches the precipitation in heavy isotopes. The amount effect is most pronounced in low-middle latitude tropical coasts and islands and is less severe when both ambient temperatures are low and when the amount of rain is large.

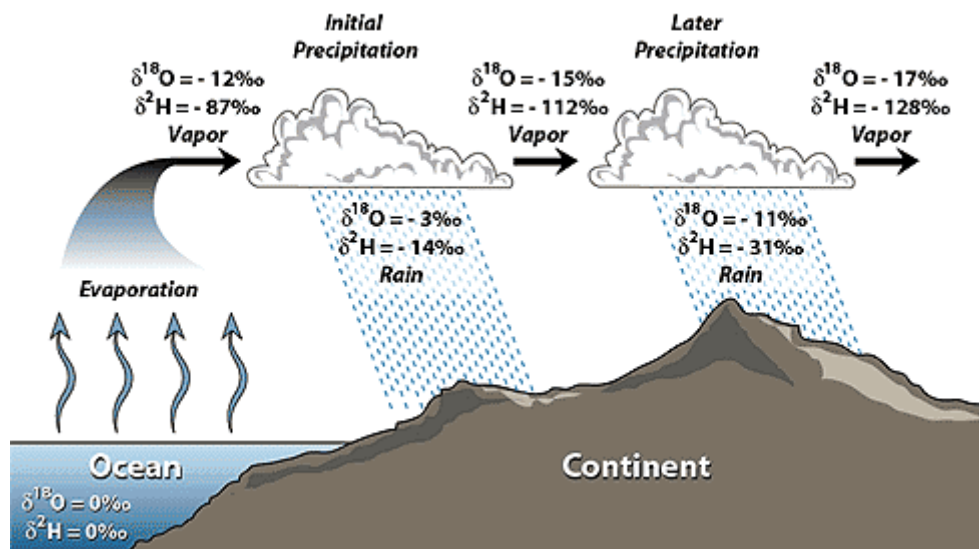


Figure 5.2: Illustration of progressive depletion of ^{18}O . As it rains, the clouds become more depleted in ^{18}O . As clouds travel further inland, they also become more depleted in ^{18}O (Data source: SAHRA, 2010).

5.3 RESULTS AND DISCUSSION

The results of the North Bank oxygen isotope survey are displayed spatially in Figure 5.3. The $\delta^{18}\text{O}$ values are expressed in units of parts per thousand (‰) in reference to V-SMOW and can be seen to range from -8.83‰ to -6.12‰ (with a measurement error of 0.1‰).

The two Wairau River samples were found to be -8.83‰ and -8.18‰ (measured one day apart) that together gave an average value of -8.51‰ (2 d.p.). These data are within analytical error of Wairau River values from other studies. Taylor et al. (1992) gave a value of -8.79 ± 0.14 ‰, Robinson and Botrell (1997) reported a value of -8.7, while Stewart (2006) found a mean of -8.78‰. Considering that the Wairau River fluctuates in oxygen isotope composition over time (for example, Taylor et al. found $\delta^{18}\text{O}$ values ranging from -7.96 to -9.56 from data spanning 20 years) the results presented here are representative of the average isotopic composition in the Wairau River.

Oxygen isotope values from tributary valleys are distinctly less negative than Wairau River samples, as found by previous studies within the Kaituna Valley (Taylor, 2004), the south side of the Wairau Valley (Taylor, 2003), and the broader Wairau Valley (Taylor et al., 1992). While Wairau River samples, and samples inferred to contain water from the Wairau River, are distinctly negative (c. -8.5‰), tributary valley samples exhibit less negative values (c. -7‰ to -6‰).

At their junction with the Wairau River, tributary valleys display $\delta^{18}\text{O}$ values closer in composition to those from the Wairau River (Figure 5.3). Waters that lie between tributary valley mean $\delta^{18}\text{O}$ values and Wairau River $\delta^{18}\text{O}$ values are inferred to be the result of mixing. The degree of mixing which occurs will depend on where the Wairau River – groundwater interface exists in relation to the sample point, and will be discussed in detail in later sections.



Northbank Oxygen Isotope Results

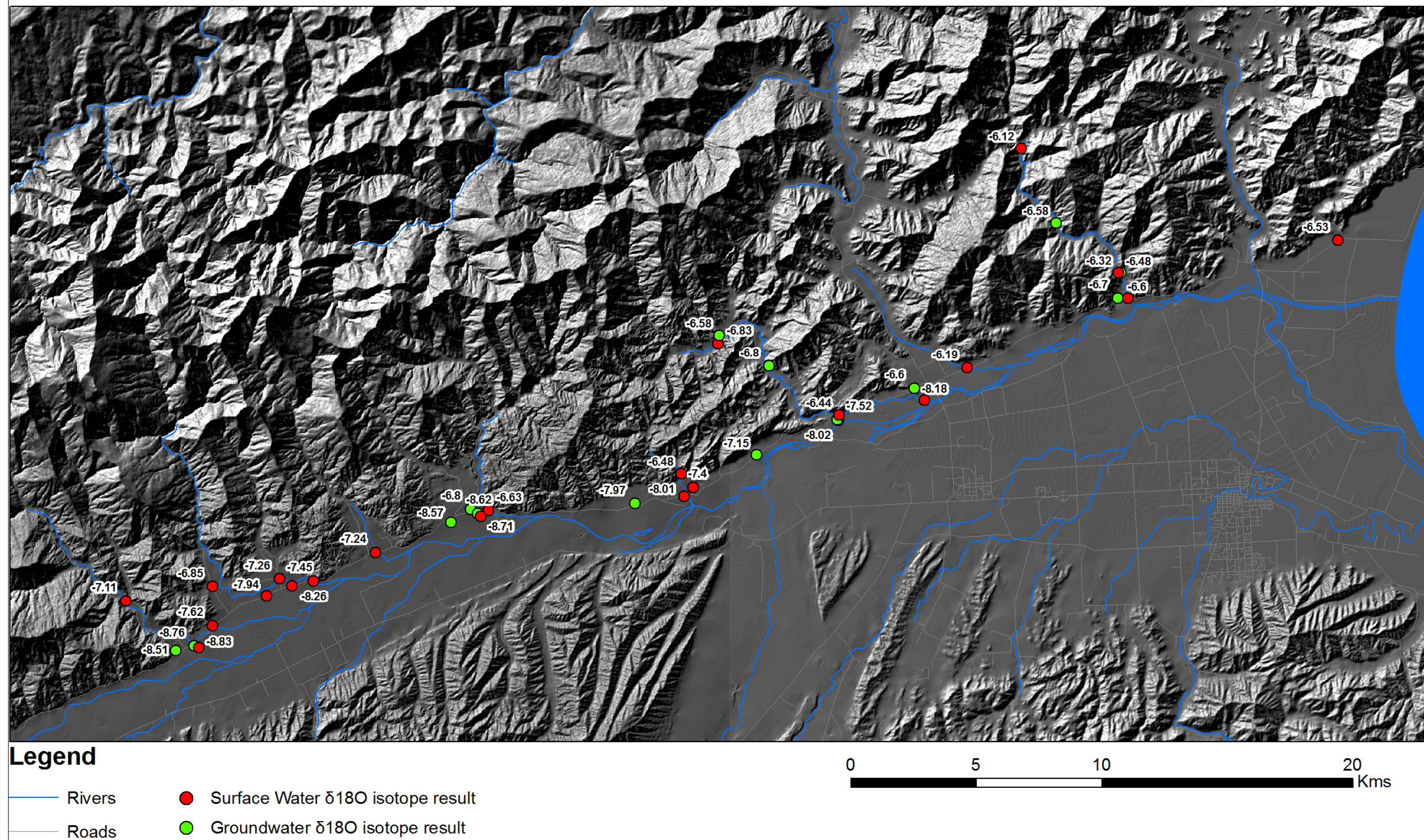


Figure 5.3: North Bank Oxygen Isotope Results from Sampling Survey August 3rd-6th 2009 (site 034 and 035 collected July 13th)

The distance to the coast and mean catchment altitude both, at first glance, appear to have an effect with an apparent trend of values becoming less negative from west to east respectively (Figure 5.3). Catchment distances from Cloudy Bay and Tasman Bay, along with mean catchment altitude are shown in Table 5.1. These were all examined in relation to the mean $\delta^{18}\text{O}$ value found for each catchment, the results of which are shown in Figure 5.4, Figure 5.5 and Figure 5.6 respectively.

Table 5.1: Catchment distances from Cloudy Bay and Tasman Bay, mean catchment altitude and mean $\delta^{18}\text{O}$ values for each catchment

* shortest route 'central catchment to Cloudy Bay' and 'central catchment to Tasman Bay'

** Estimated from mean of minimum and maximum catchment altitude

Catchment	Distance from Cloudy Bay (km)*	Distance from Tasman Bay (km)*	Mean Altitude (m)**	Average $\delta^{18}\text{O}$ value
Top Valley	55	26	900	-7.37
Timms Creek	49	30	850	-7.26
Cat Creek	45	33	600	-
Burnt Scrub Creek	49	35	400	-6.85
Pine Valley	43	32	850	-7.24
Fabian's Valley Bartlett's Creek	-	-	-	-
<i>Fabian's & Bartlett's Total</i>	37.5	35	700	-6.72
Swamp Gully	30	40	350	-6.48
Onamalutu Valley	27	38	640	-6.66
Kaituna Valley	21	41	340	-6.40
Waikakaho Valley	14	42	480	-6.47
Pukaka Valley	4	50	470	-6.53

Plotting catchment distance from Cloudy Bay and Tasman Bay respectively versus mean catchment $\delta^{18}\text{O}$ values yielded a strong correlation for each. The distance from Cloudy Bay gave a moderately strong correlation ($R^2 = 0.68$, Figure 5.4) where increasing distance from the bay results in increasingly negative $\delta^{18}\text{O}$ values, in accordance with the continental effect (5.2.4). The distance from Tasman Bay gave a slightly stronger correlation ($R^2 = 0.75$, Figure 5.5) although increasing distance from the bay results in less negative $\delta^{18}\text{O}$ values, which is not in accordance with the continental effect.

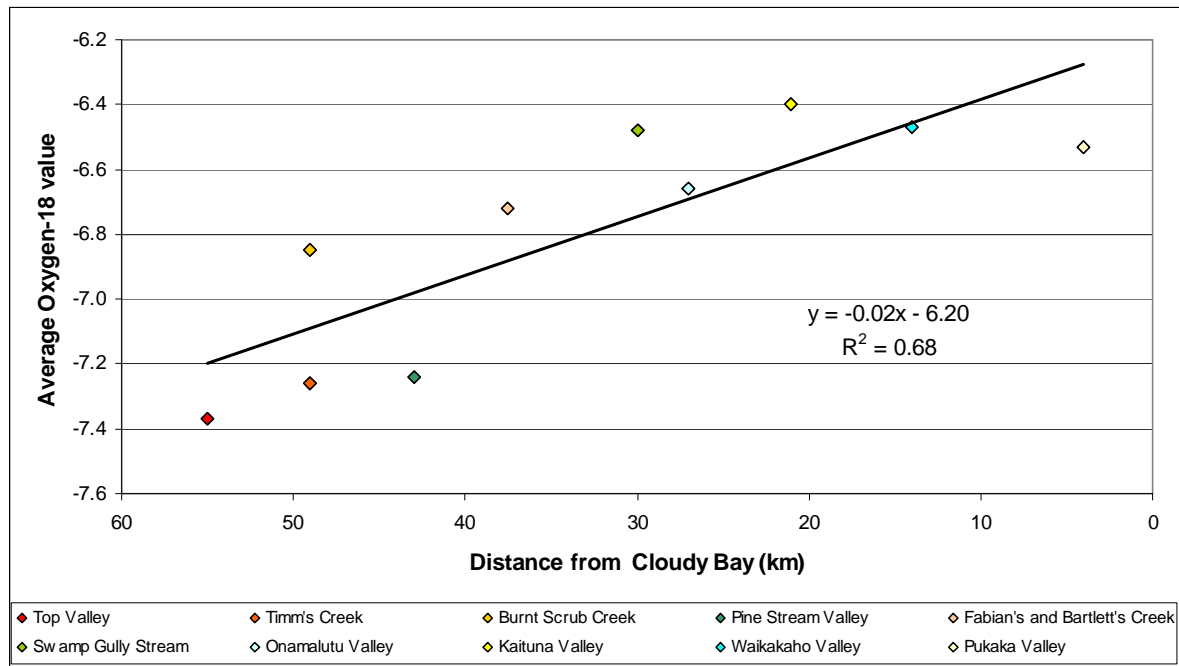


Figure 5.4: Distance from Cloudy Bay versus average catchment Oxygen-18 value.

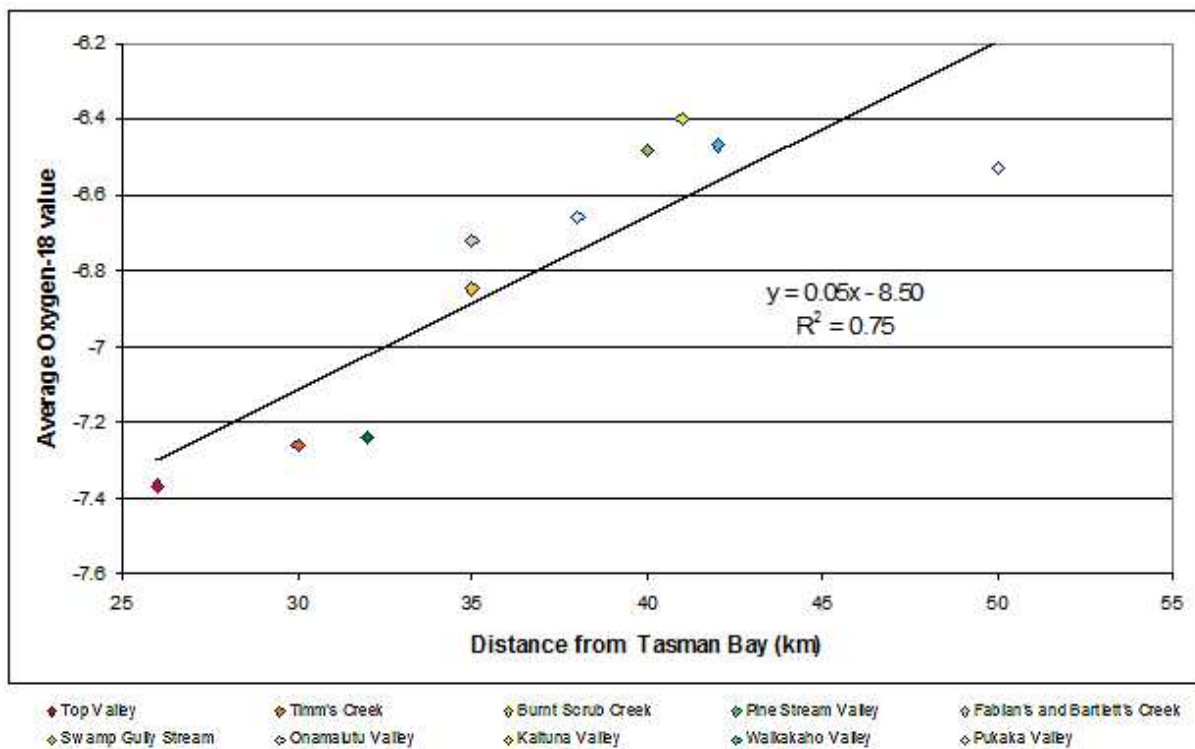


Figure 5.5: Distance from Tasman Bay versus average catchment Oxygen-18 value.

In demonstrating the expected relationship, distance from Cloudy Bay could be the more important factor in determining mean catchment $\delta^{18}\text{O}$ values rather than distance from Tasman Bay. However, as the of source most precipitation for the North Bank is expected to come from the northwest (from the direction of Tasman Bay), it would be expected for

$\delta^{18}\text{O}$ values to become increasingly negative west to east respectively if the continental effect was an important factor. As $\delta^{18}\text{O}$ values did not follow that trend, the continental effect is not deemed to be an important factor.

Plotting mean catchment altitude in relation to average oxygen-18 values yielded the strongest correlation where the higher the mean catchment altitude, the increasingly negative the $\delta^{18}\text{O}$ value, in accordance with the altitude effect (5.2.3). This correlation was moderately strong ($R^2 = 0.77$, Figure 5.6) and indicates that mean catchment altitude is the most important factor influencing $\delta^{18}\text{O}$ values.

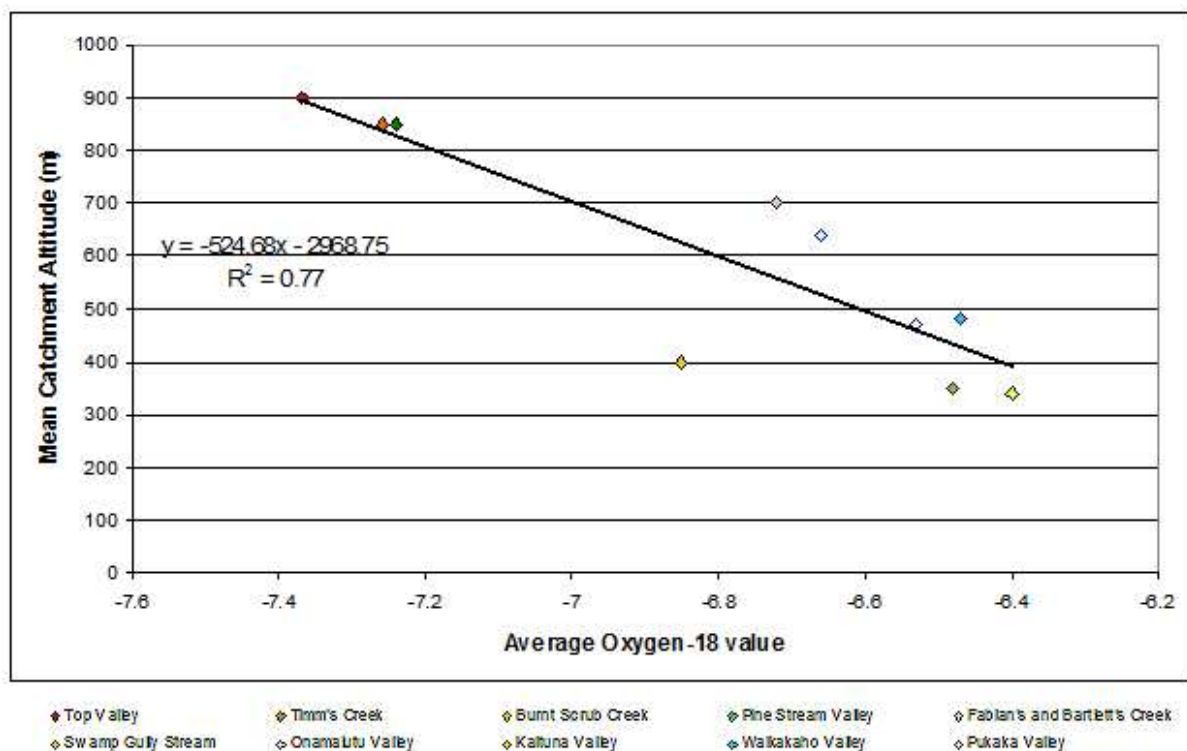


Figure 5.6: Average oxygen-18 value versus mean catchment altitude.

The effect of mean catchment altitude appears to be important in controlling $\delta^{18}\text{O}$ values found on the North Bank. This is reasonable within the New Zealand setting as often extreme topography is present within a short distance from water vapour's oceanic source. The strong correlations between distance from the coast and $\delta^{18}\text{O}$ values displayed in both Figure 5.4 and Figure 5.5 are coincident with the effect of altitude. It is expected that the majority of precipitation upon the North Bank will be sourced from the northwest, however, the altitude effect will be the controlling factor rather than any effect of continentality.

Ground and surface water data are commonly plotted on a $\delta D - \delta^{18}O$ diagram such as those presented in Figure 5.7 and Figure 5.8, along with the GMWL for reference. The trend line for surface water and groundwater is defined by the relationship $\delta D = 7.9 \delta^{18}O + 11.0$ and $\delta D = 8.0 \delta^{18}O + 11.9$ respectively, and shows minimal modification from the Global trend (GMWL) as defined by Craig (1961). Taylor et al. (1992) also demonstrated a regular relationship between $\delta^{18}O$ and δD for the Wairau Valley and Plains, very similar to Craig's mean global line.

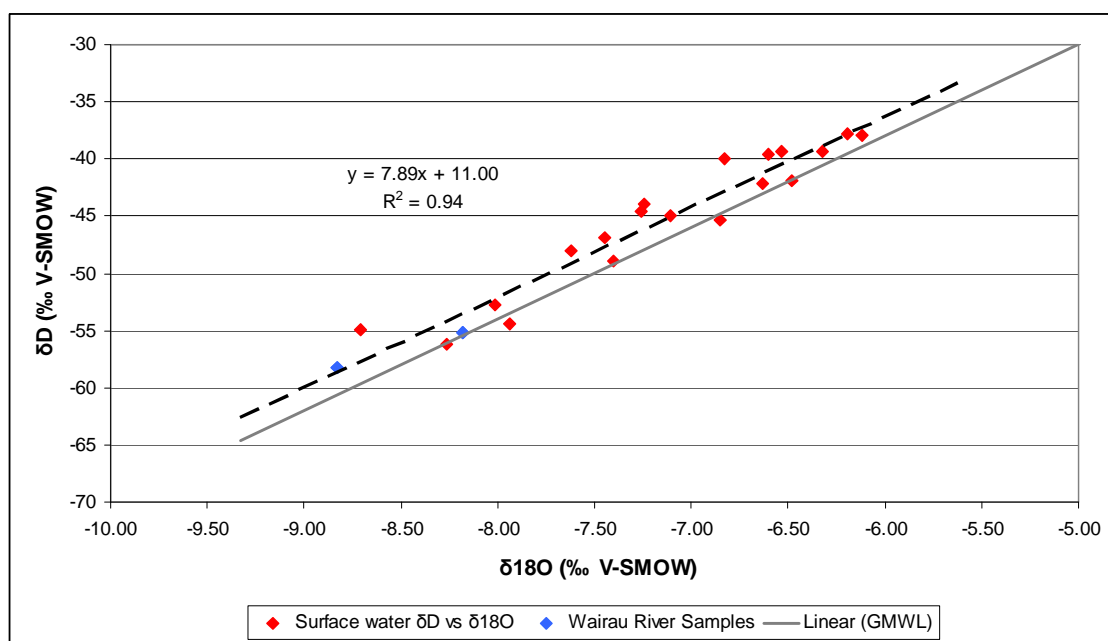


Figure 5.7: Relationship of δD to $\delta^{18}O$ determined by surface water samples collected 2009. Solid trend line represents GMWL for reference.

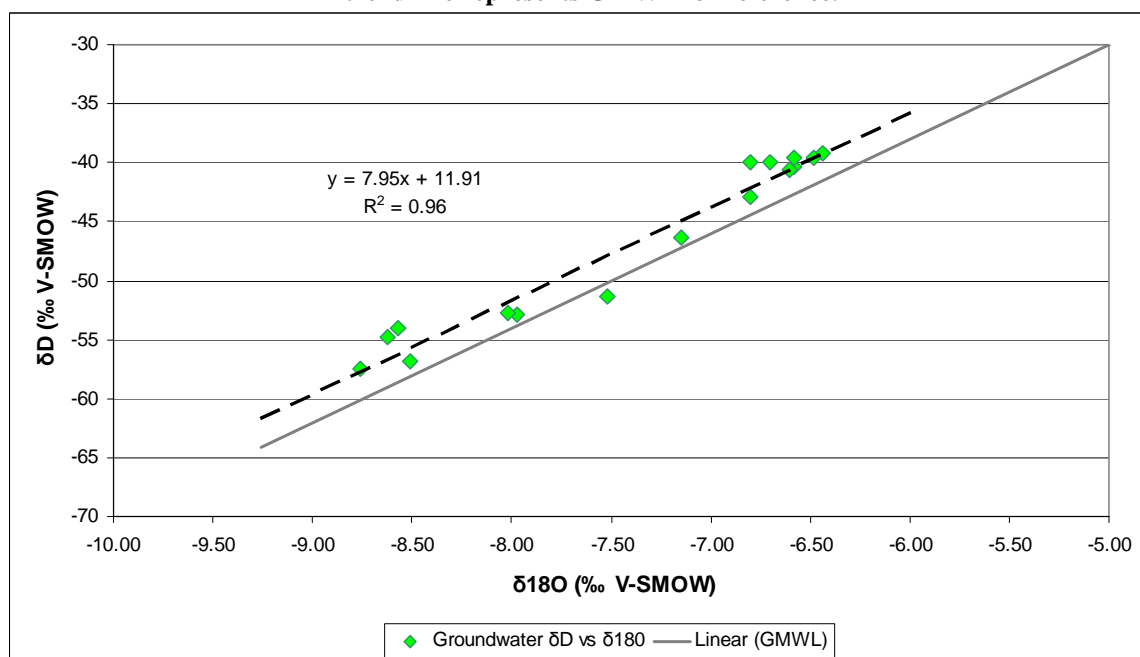


Figure 5.8: Relationship of δD to $\delta^{18}O$ determined by groundwater samples collected 2009. Solid trend line represents GMWL for reference.

The close alignment and proximity of stable isotope data for the North Bank compared to the GMWL indicates little modification by evaporation as this phenomenon would result in data plotting further away from the GMWL. Figure 5.9 depicts how deviation from the GMWL would occur for a given water sample if evaporation took place. As no clear evaporation trend can be seen from the data collected by this study in Figure 5.7 or Figure 5.8, it is inferred that evaporation is not occurring to any appreciable extent for groundwaters or surface waters upon the North Bank. An interesting feature is instead a clustering of groundwater data points in Figure 5.8 at $\delta^{18}\text{O}$ values of around -8.50 ‰ and another cluster of around -6.50 ‰. This is a consequence of Wairau River water and groundwater sourced from North Bank tributaries separating into two groups. Wairau River waters are significantly more negative in $\delta^{18}\text{O}$ (-8.50 ‰) than North Bank tributaries (-6.50 ‰). Data points that lie between these two clusters can be regarded as mixed-water.

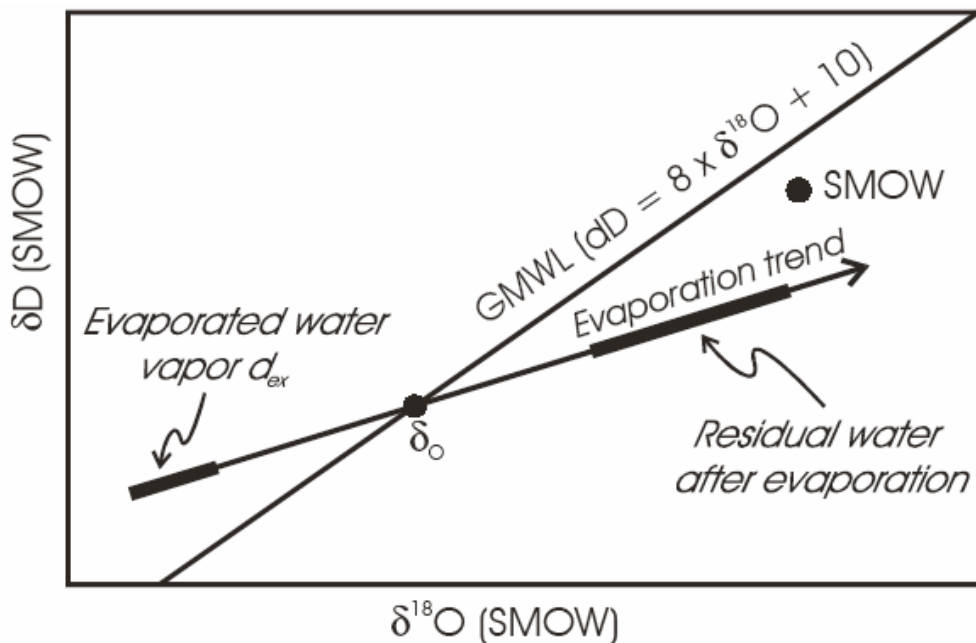


Figure 5.9: $\delta^{18}\text{O}$ versus δD . Effect of kinetic fractionations of evaporation and condensation on water is shown. Water starts on the GMWL with a δ value of δ_0 . During evaporation, residual water moves to the right of the GMWL while vapour lies to the left to preserve mass balance. Water vapour which then condensates will have a composition of d_{ex} , and mixing of this water with any other water on the GMWL will produce waters above the meteoric water line (Gat, 1996).

Inspection of the two data sets (Figure 5.7 and Figure 5.8), reveals waters are consistently above the meteoric water line which may point to an influence by relative humidity.

Vapour for precipitation sourced from an arid vapour region where humidity is low would result in a high deuterium excess (d), upwards of 20. In contrast, d values for humid regions will be low, approaching zero. In this way, the d value is a useful parameter in

identifying vapour source regions. The d values encountered here are both around 11 which suggest that the vapour source is neither especially arid nor humid.

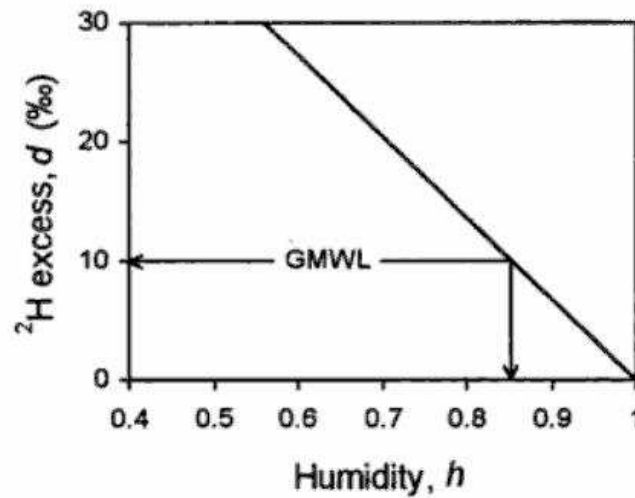


Figure 5.10: Humidity versus Deuterium excess (Clark and Fritz, 1997).

The d -excess values determined in this study (i.e. 11 and 11.9 for surface water and groundwater respectively) are higher than the value of 10.8 used for the GMWL and that used for other easterly climatic zones such as Canterbury and Otago. With reference to Figure 5.10, d values of 11 and 11.9 correspond closer to 80 percent humidity, less than the global average of 85 percent. A slightly lower relative humidity from the global mean at the source of water vapour is offered as the reason behind the slightly higher than average d -excess for both surface water and groundwater, and in turn, the reason for waters consistently plotting above the meteoric water line in Figure 5.7 and Figure 5.8. This would be consistent with the rain shadow effect of the Southern Alps causing moisture depletion from south-easterly or westerly air masses in much the same way as the Southern Alps indirectly lower $\delta^{18}\text{O}$ composition (Stewart and Morgenstern, 2001). As a result of their altitude, the Southern Alps promote orographic rainfall in which heavy isotopes are preferentially rained out first so that rainfall thereafter is progressively lighter in ^{18}O . Parallel to that, lower $\delta^{18}\text{O}$ values are brought about through Rayleigh fractionation driven by altitudinal effects.

An overall description of the oxygen isotopic picture upon the North Bank is that water vapour, coming predominantly from Tasman Bay to the North West and with a $\delta^{18}\text{O}$ composition of around -2 ‰ for initial rainfall, is swept over the 800-1200 m tall Richmond Range with the altitude effect lowering $\delta^{18}\text{O}$ values to around -6 ‰ to -7 ‰ for

subsequent rainfall. In comparison, Wairau River water, sourced from a high altitude alpine catchment has more negative $\delta^{18}\text{O}$ values of approximately -8.8 ‰, principally due to the greater altitude effect experienced in an alpine environment.

The distinct isotopic difference between the signature of waters of the Wairau River and waters that arrive more locally at lower elevation provides an ability to determine groundwater origin and direction of flow. As Wairau River samples, and samples inferred to contain water that came from the Wairau River, are markedly negative at around -8.5‰ and tributary valley samples are circa -6‰ to -7‰, the contrast in isotope values allows identification of the source and the degree of mixing.

5.4 CONSTRAINT OF THE WAIRAU RIVER – GROUNDWATER INTERFACE

The Wairau River – groundwater interface on the North Bank can be identified through the distinct isotopic difference that exists between waters of the Wairau River and waters of the North Bank. The spatial position of the interface will be determined and presented here for those valleys which are not case study areas. These are specifically the Onamalutu and Kaituna Valleys, the Langley-dale/Coatbridge area, Bartlett's Creek, Pine Stream Valley and Pukaka Drain.

Figure 5.11 displays the oxygen isotope results from Onamalutu and Kaituna Valleys from the sampling survey carried out August 3rd to 6th, 2009. Onamalutu Valley was found to have an average $\delta^{18}\text{O}$ value of -6.66 ‰ with all Onamalutu values within 0.17 ‰ of this mean value. The groundwater and surface water sample pairing located in the upper middle reaches of the Onamalutu Valley both share similar values (-6.58 ‰ and -6.83 ‰ respectively) which, in combination with their similar water chemistry (Chapter 4), indicates that groundwater receives recharge principally from surface water, and that they are geochemically indistinct. The slight variation present is likely due to the waters corresponding to different rainfall events and the natural variability in water oxygen isotope composition over time. Corollary to this, groundwater residence time can be expected to be of the order of roughly 1 year (based on groundwater residence time for the Waikakaho Valley) while channel flow may only be several months old.

Onamalutu and Kaituna Valleys Oxygen Isotope Results

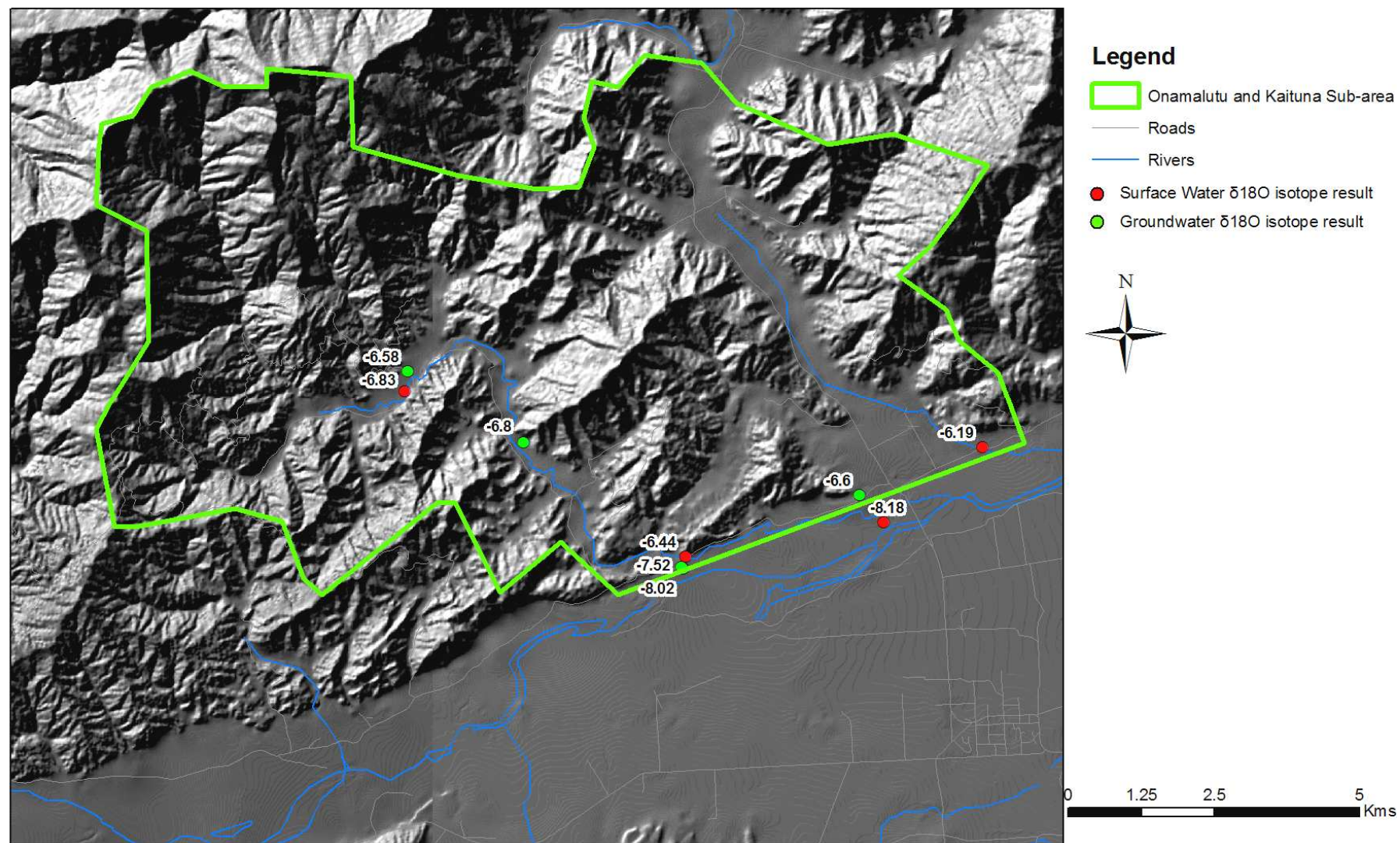


Figure 5.11: Onamalutu and Kaituna Valleys Oxygen Isotope Results from Sampling Survey August 3rd-6th 2009

At the junction of Onamalutu Valley and the Wairau Valley, $\delta^{18}\text{O}$ values become more negative, closer to the $\delta^{18}\text{O}$ value of the Wairau River (-8.18 ‰). Figure 5.12 demonstrates how the oxygen isotope signature changes from -6.44 ‰ measured from the Onamalutu River, to a groundwater sample of -7.52 ‰ measured 200 metres to the south at well P28w/4907 to -8.02 ‰ another 40 metres south at well P28w/4906, and finally -8.18 ‰ at the Wairau River. This gradual decrease in $\delta^{18}\text{O}$ values across the area suggests a mixing effect of waters from the Onamalutu River and Wairau Rivers respectively with the Wairau River – groundwater interface regarded as similarly gradational in nature. The red line denotes an estimated limit on the extent of influence by the Wairau River. This limit is situated closer to the Onamalutu River than the Wairau River as a difference of circa -1.8 ‰ exists in total between the Wairau and Onamalutu Rivers while groundwaters are still significantly negative (by -1.1 ‰) only 200 metres from the Onamalutu River. The estimated limit is shown to follow geomorphology as geomorphology likely plays an important role in groundwater movement and any mixing that would occur.

North of the estimated limit, Wairau River waters would not be expected to be detected due to the landform being the floodplain of the Onamalutu River. There, groundwater sourced from the Onamalutu River would be expected to dominate. West of the estimated limit, not enough data exists to infer what water predominates, however, with a schist/greywacke bedrock high forming a boundary between the Wairau and Onamalutu Rivers, it is reasonable to assume the Onamalutu River dominates groundwater recharge.

The three samples collected from Kaituna Valley are displayed in relation to geology and geomorphology in Figure 5.13. The $\delta^{18}\text{O}$ value of the Wairau River (-8.18 ‰) can be seen to be significantly more negative than either the $\delta^{18}\text{O}$ groundwater value from well P28w/3923 (-6.6 ‰) or the surface water sample from Are Are Creek (-6.19 ‰). This is consistent with a past oxygen isotope survey carried out in the Kaituna area where both upper terrace waters (Q2 Kaituna Terrace) and groundwater in the lower terrace closer to the Wairau channel had $\delta^{18}\text{O}$ values between -6.0 ‰ and -7.1 ‰, while the Wairau River was considerably more negative at - 8.34 ‰ (Taylor, 2004). The flow rate of the Wairau River during the 2004 oxygen isotope survey was between 20 and 200 cumecs as recorded downstream at Tuamarina.

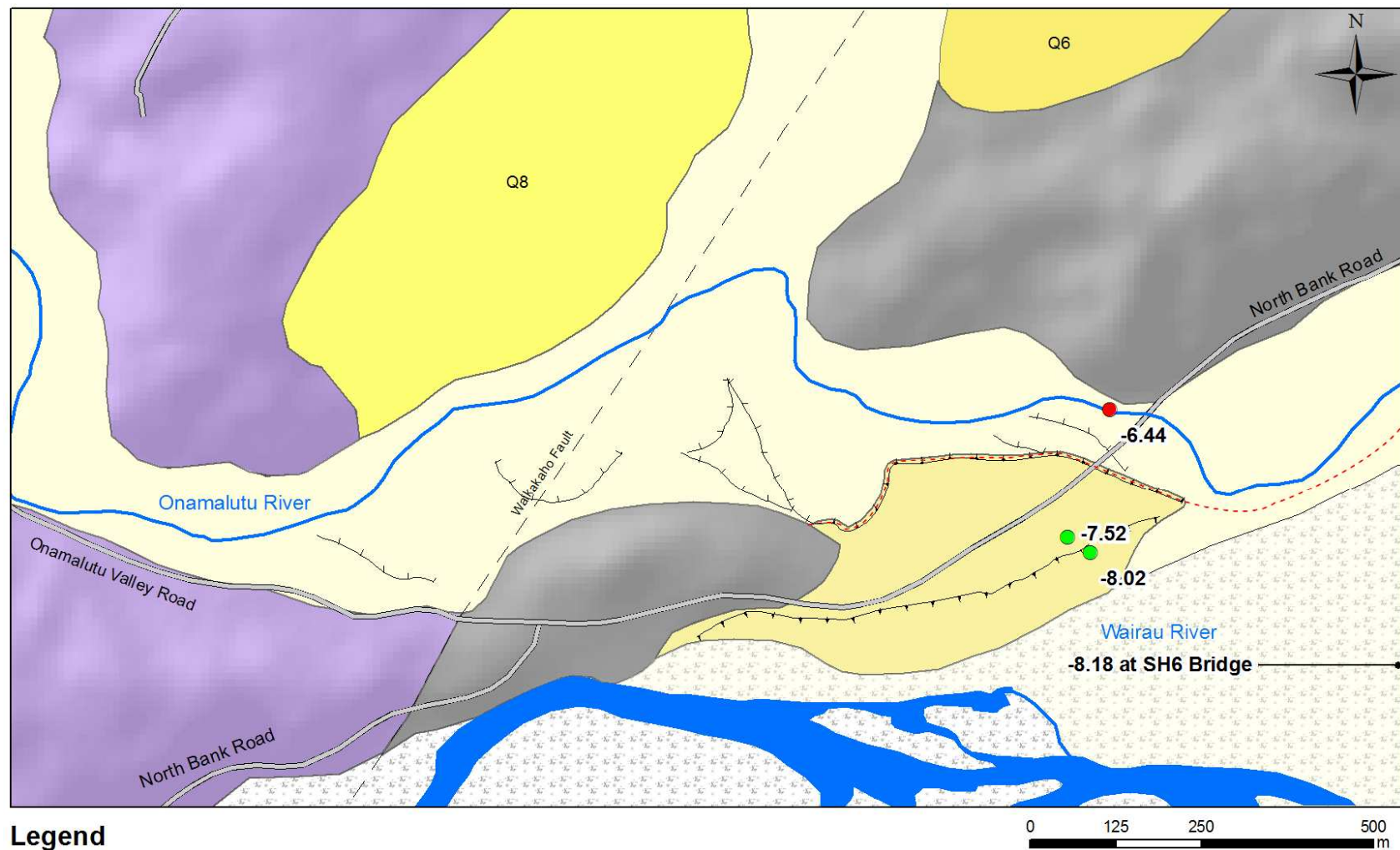
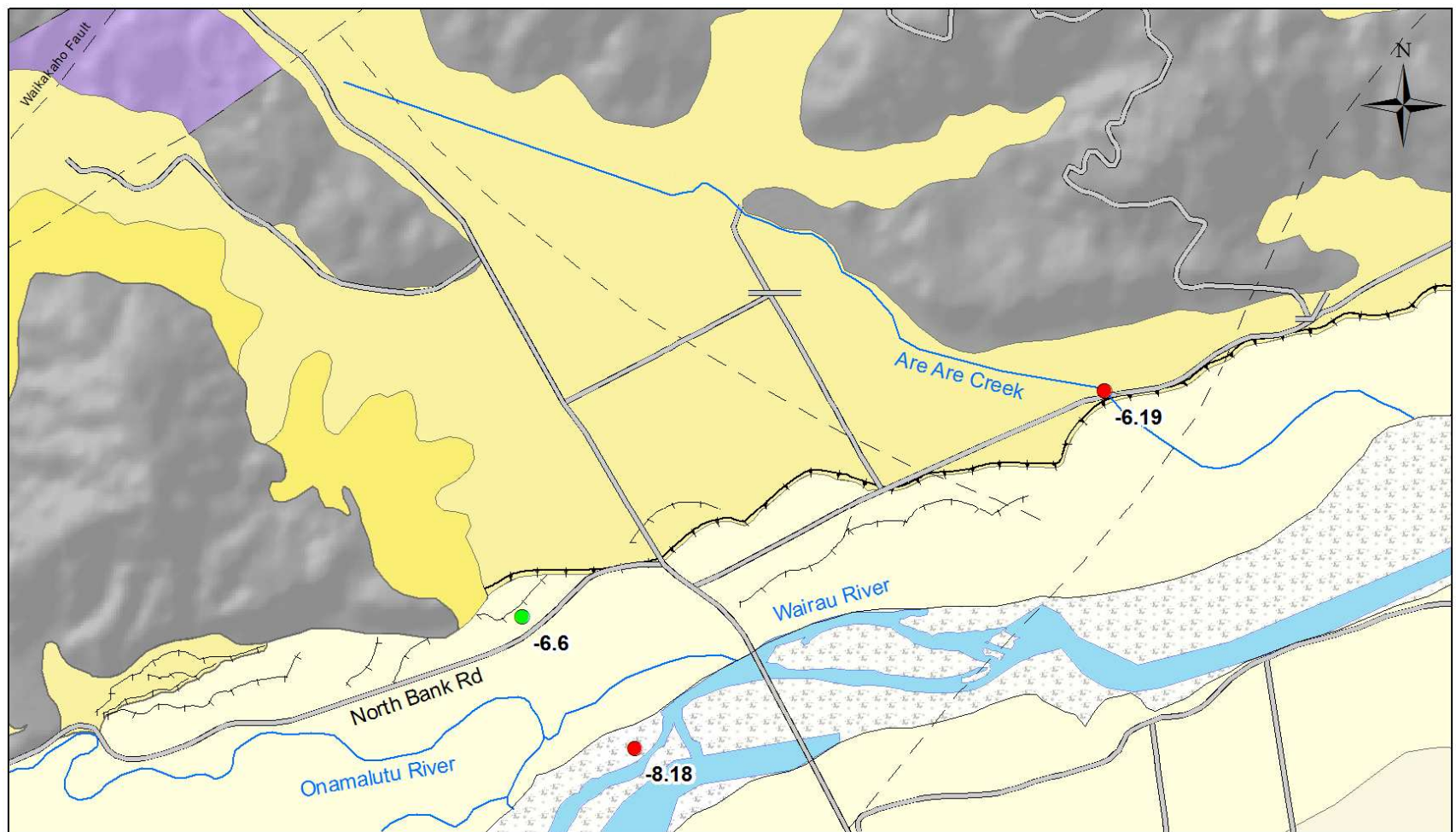


Figure 5.12: Oxygen isotope values at junction of Onamalutu and Wairau Valleys in relation to geology and geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River. A mixing zone exists between the red line and the Wairau River.

On the basis of the $\delta^{18}\text{O}$ signature of the Wairau River being appreciably more negative, any mixing of Wairau River water with waters from North Bank tributaries should be easily discernable. In light of the $\delta^{18}\text{O}$ values lying consistently between -6.0 ‰ and -7.1 ‰, the influence of the Wairau River was deemed to be less extensive than previously thought (Taylor, 2004). This study is compared to an oxygen isotope survey carried out by MDC, 26-27 February, 2007, where $\delta^{18}\text{O}$ values similar to this study were found at well P28w/3923 (-6.58 ‰), Are Are Creek (-6.19 ‰), the Onamalutu River (-6.41 ‰) and the Wairau River (-8.07 ‰). An additional oxygen isotope survey was carried out by MDC in October 2007 (when the Wairau River flow rate was 500-1000 cumecs), however, the $\delta^{18}\text{O}$ values collected by this study best agree with the data from the February oxygen isotope survey (when the Wairau River flow rate was 20-45 m³/sec, similar to the flow rate during this study of 37-56 cumecs). Subsequently, Figure 5.11 draws upon the oxygen isotope data gathered by the February oxygen isotope survey in order to draw an oxygen isotope picture of the Kaituna area.

Prior to Taylor's (2004) findings, the prominent terrace that separates the Q2 Speargrass Formation from the lower Q1 Rapaura Formation was thought to be an obvious limit of influence by the Wairau River. However, examination of Figure 5.14 reveals the Wairau River's influence appears to be limited closer to its own channel. The red line denotes an estimated limit on the extent of influence by the Wairau River and is drawn equidistant between the Wairau River channel and the closest groundwater wells. As the closest groundwater wells give $\delta^{18}\text{O}$ values characteristic of North Bank-derived water, the estimated limit of Wairau River influence is interpreted as lying somewhere between these wells and the Wairau River's own channel. The implications of these findings indicate that Kaituna groundwater is recharged predominately from local rainfall with very little influence from Wairau River seepage, even for wells located within the Wairau River gravels on the south side of the northern terrace scarp (PDP, 2008). Interesting to note is that even with flow conditions of the Wairau River varying between 20 cumecs and 1500 cumecs, the Wairau River gives no indication of groundwater recharge to wells on the lower terrace. Taylor (2004) surmises that the Wairau River is not contributing significantly to the groundwater in the terraces in the Kaituna area with this study confirming values found for well P28w/3923, Are Are Creek, Onamalutu River and the Wairau River.



Legend

- Roads
- Terrace Edges (0-2 metres)
- Rivers
- Terrace Edges (2-3 metres)
- Faults

- Q1 Floodplain & Recent Alluvium
- Q2 Kaituna Terrace
- Q6 Kaituna Valley

- Schist Kaituna
- Greywacke Kaituna

0 0.25 0.5 1 Kms

- Surface Water $\delta^{18}\text{O}$ isotope result
- Groundwater $\delta^{18}\text{O}$ isotope result

Figure 5.13: Oxygen isotope values at junction of Kaituna and Wairau Valleys in relation to geology and geomorphology



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Figure 5.15 broadly displays the oxygen isotope results from the Pine Valley, Bartlett's Creek and Coatbridge/Langley-dale areas. A similar trend of distinctly less negative $\delta^{18}\text{O}$ values from tributary valleys was found (-6.48 ‰ to -7.4 ‰) compared to Wairau River samples (circa -8.5 ‰). Only a single surface water sample was collected for Pine Valley in the absence of groundwater wells, and which yielded a $\delta^{18}\text{O}$ value of -7.24 ‰. This was moderately more negative than the average $\delta^{18}\text{O}$ value of -6.72 ‰ for Fabian's Valley and Bartlett's Creek and could be a function of the higher mean catchment altitude of Pine Valley (850m asl) compared to that of Fabian's Valley and Bartlett's Creek (700m asl). The Coatbridge/Langley-dale area demonstrated a suitably less negative $\delta^{18}\text{O}$ value from the low mean catchment altitude area of Swamp Gully Stream (-6.48 ‰ and 300m asl respectively) with other $\delta^{18}\text{O}$ values more negative closer to the Wairau River.

The sole sample collected from Pine Valley is displayed in relation to geology and geomorphology in Figure 5.16. Despite its location upon the low-lying Q1 Floodplain relatively close to the Wairau River, the $\delta^{18}\text{O}$ signature is characteristic of local precipitation or surface water from low-altitude hills rather than the Wairau River signature which stems from a high-altitude catchment. In the absence of any groundwater data, it is difficult to constrain the extent of the Wairau River – groundwater interface within Pine Valley. On the basis of the $\delta^{18}\text{O}$ value from Pine Valley Stream, the only assertion that can confidently be made is that influence by the Wairau River upon the $\delta^{18}\text{O}$ signature of Pine Valley Stream is minimal. While the prominent Q2 terrace in Pine Valley places an obvious geomorphologic limit on the extent of influence by the Wairau River, it is suggested that any Wairau River influence is more limited in extent, with any recharge contribution to groundwater occurring principally within Q1 Rapaura Formation alluvium close to the Wairau River channel.

Pine Valley, Bartlett's Creek & Coatbridge/Langley-dale Oxygen Isotope Results

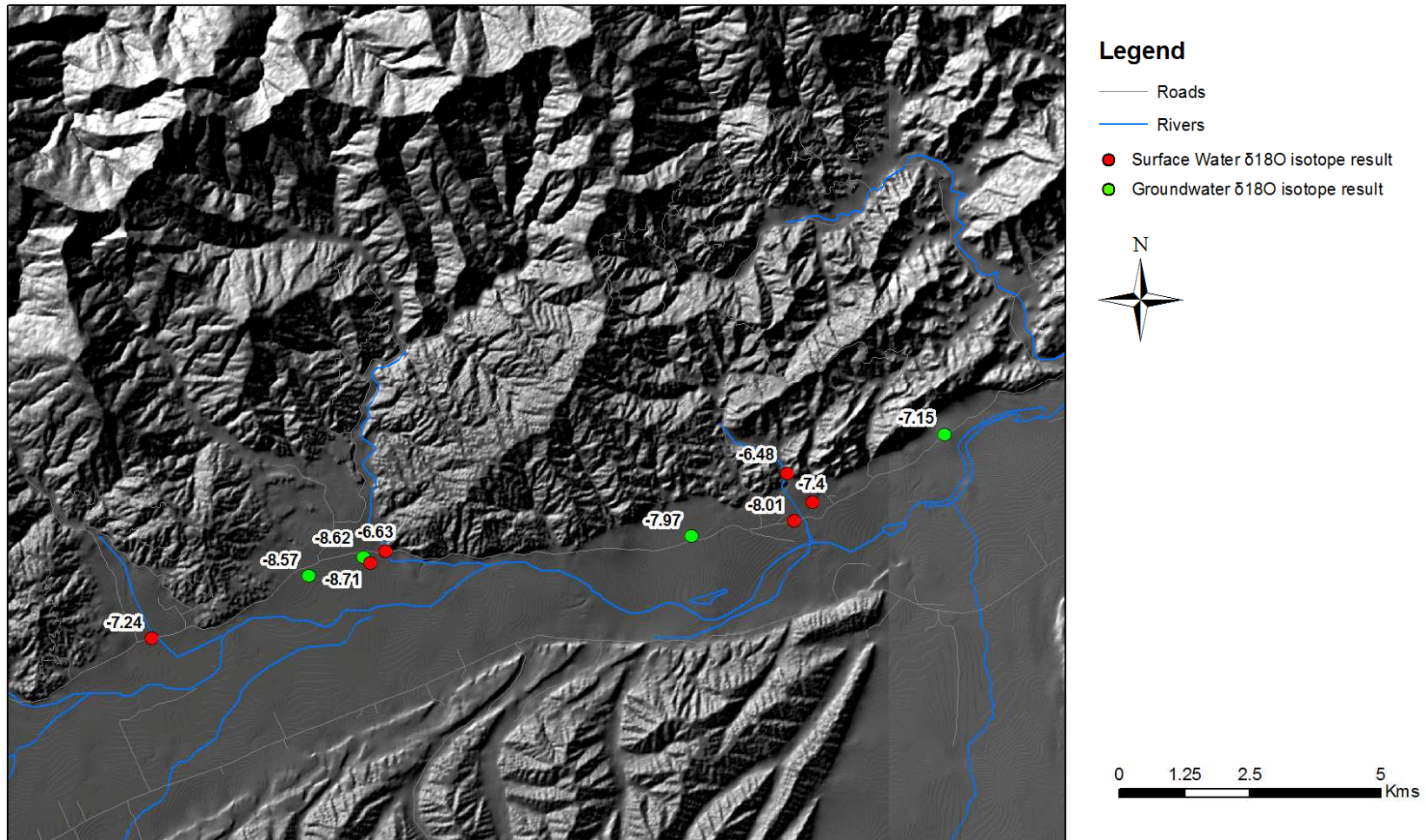
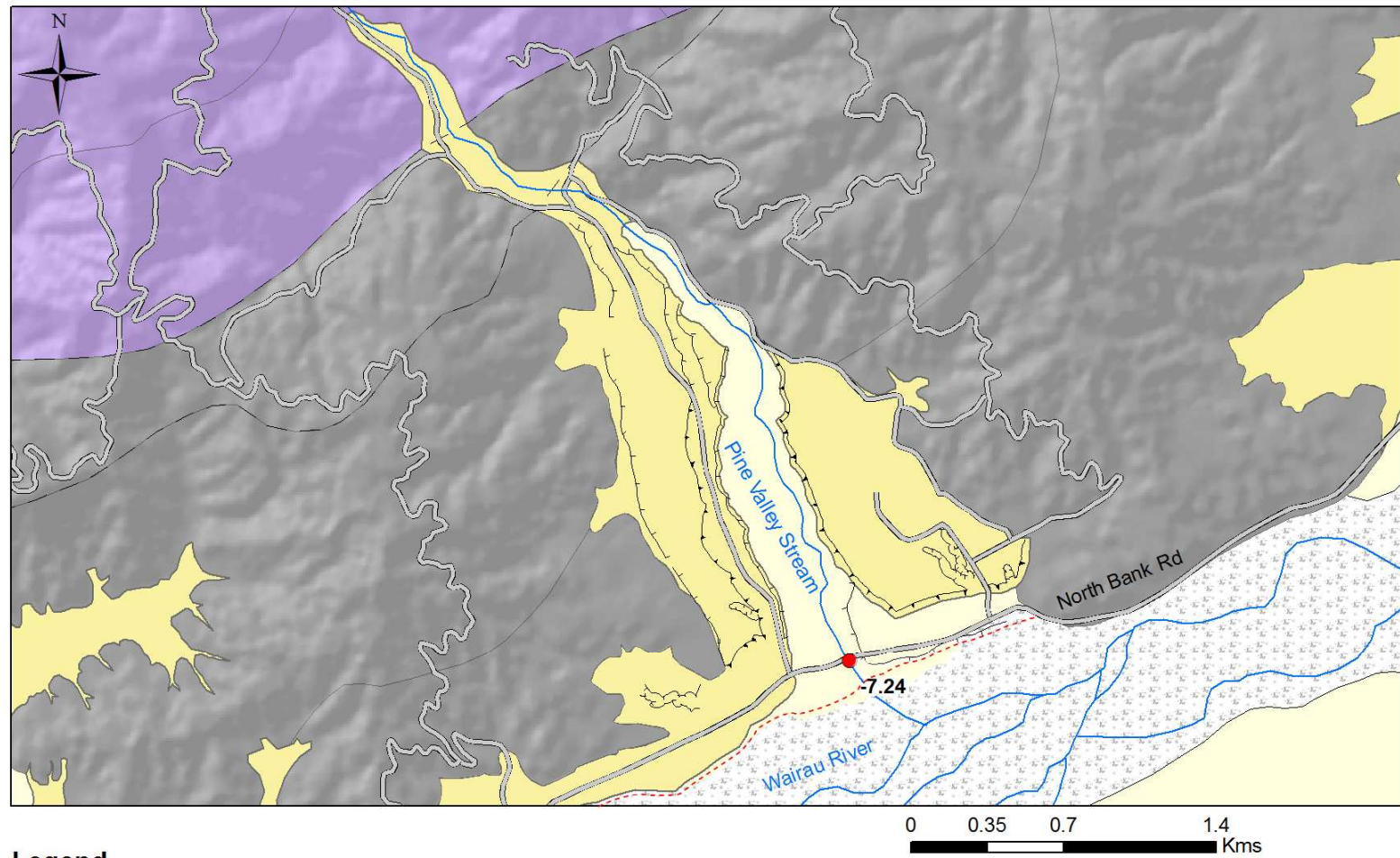


Figure 5.15: Pine Valley, Bartlett's Creek and Coatbridge/Langley-dale Oxygen Isotope Results from Sampling Survey August 3rd-6th 2009



Legend

- | | | | | |
|----------|------------------------------|---------------------------------|-----------------------|--|
| — Roads | — Terrace Edges (0-2 metres) | Q1 Floodplain & Recent Alluvium | Schist Pine Valley | ● Surface Water $\delta^{18}\text{O}$ isotope result |
| — Rivers | — Terrace Edges (2-4 metres) | Q2 Terrace Pine Valley | Greywacke Pine Valley | ● Groundwater $\delta^{18}\text{O}$ isotope result |
| — Faults | | | | |

Figure 5.16: Oxygen Isotope value for Pine Valley in relation to geology and geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River.

Oxygen isotope values collected from Fabian's Valley and Bartlett's Creek are displayed in relation to geology and geomorphology in Figure 5.17. With the benefit of more groundwater wells available than other North Bank tributaries in this section, a clearer picture of the Wairau River – groundwater interface is able to be drawn. The $\delta^{18}\text{O}$ value found for Bartlett's Creek at North Bank Road was -6.63 ‰ and can be regarded as characteristic of North Bank tributary-derived waters within Fabian's Valley and Bartlett's Creek. A groundwater sample of -6.8 ‰ was found close to the Q2 terrace, situated within Q1 Rapaura Formation alluvium. As this sample bears the $\delta^{18}\text{O}$ signature of groundwater sourced from the North Bank hills, the influence of North Bank groundwater can be inferred to extend down gradient further than the Q2 terrace scarp and into within Q1 alluvium. South of North Bank Road, all surface water and groundwater $\delta^{18}\text{O}$ values are significantly more negative and can be inferred to contain water sourced from the Wairau River. A possible degree of mixing may be evident on the diagonal transect between the groundwater sample of -6.8 ‰, the groundwater sample of -8.62 ‰, and the surface water sample of -8.71 ‰. A cautionary note is that measurement error (0.1‰) may account for the difference in these latter two values, however, it seems reasonable for a gradational Wairau River – groundwater interface to exist, similar to Onamalutu Valley. The groundwater sample of -8.57 ‰ located in the western end of the junction of Fabian's Valley and Bartlett's Creek with the Wairau River clearly receives recharge principally from the Wairau River and indicates that the limit of the Wairau River – groundwater interface lies north of this point, closer to the Q2 terrace scarp.

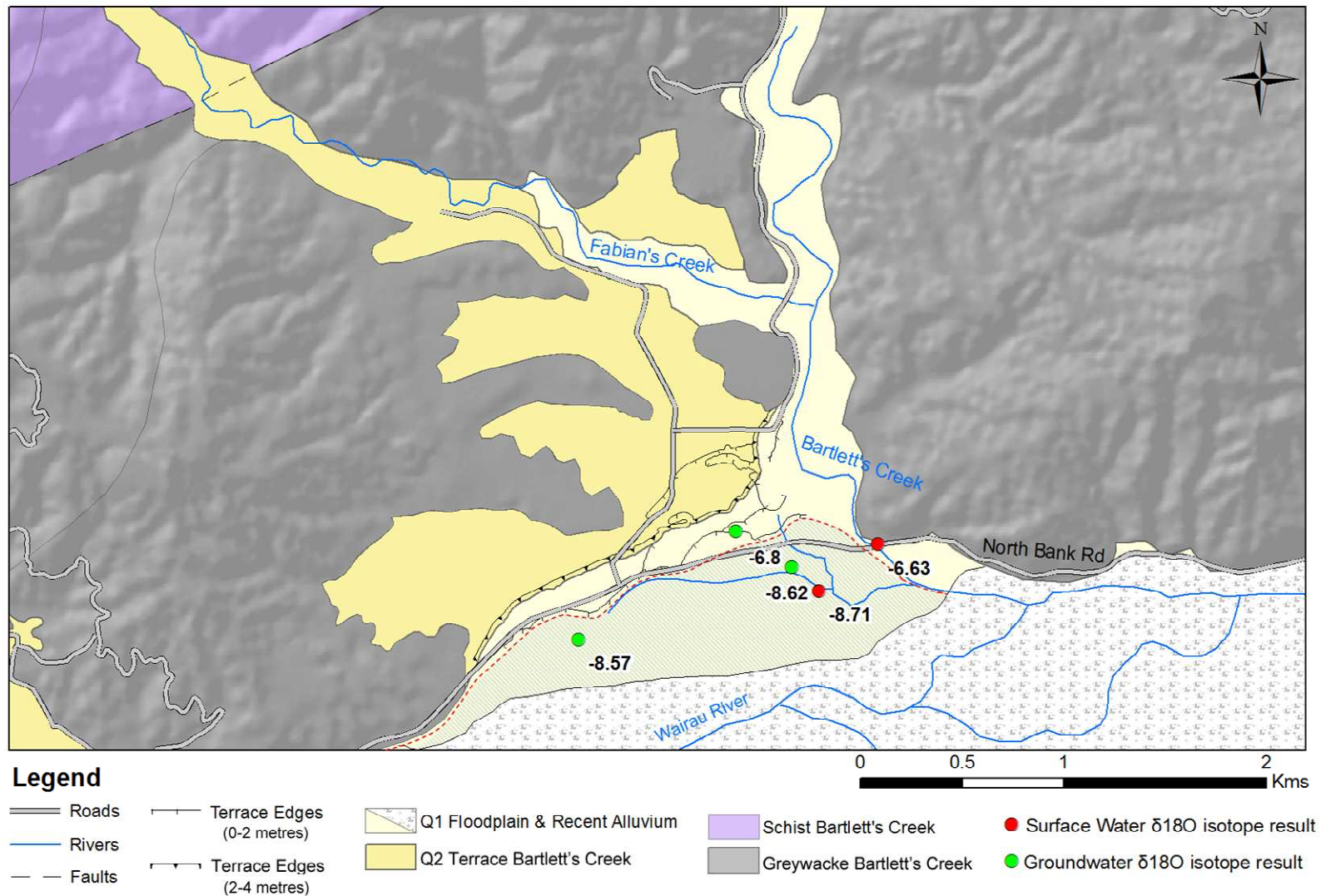


Figure 5.17: Oxygen Isotope value for Bartlett's Creek in relation to geology and geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River. The shaded area represents the mixing zone between the red line and the Wairau River

Oxygen isotope values collected from the Coatbridge/Langley-dale area are displayed in relation to geology and geomorphology in Figure 5.18. Waters inferred to come from local precipitation or from low-altitude North Bank hill country display $\delta^{18}\text{O}$ values in the range -6.48 ‰ to -7.15 ‰. These are located primarily on the Q2 terrace with the Q2 terrace scarp providing a geomorphic boundary on the extent of influence by the Wairau River. South of the Q2 terrace scarp, upon Q1 Rapaura Formation alluvium, $\delta^{18}\text{O}$ values are significantly more negative (-7.4 ‰ to -8.0 ‰), although not as negative as the $\delta^{18}\text{O}$ signature of the Wairau River (c. -8.5 ‰). This suggests that mixing of waters sourced from the North Bank with water sourced from the Wairau River is taking place with the limit of influence by the Wairau River coinciding with the Q2 terrace scarp. The surface water sample that gave a $\delta^{18}\text{O}$ value of -7.4 ‰ came from a spring located at the base of the Q2 terrace scarp. While the spring appears to emanate from the Q2 terrace (and be expected to contain waters chiefly from a North Bank aquifer), it is possible that some influence by the Wairau River is taking place. This is suggested on the bases of an oxygen isotopic value of -7.4 ‰ lying somewhere between that of North Bank tributary-derived waters and the Wairau River, and the location of other samples displaying Wairau River-influence proximal to the Q2 terrace scarp (-8.01 ‰ and -7.97 ‰). If an influence is occurring, then the small water body at the base of the terrace scarp may be a collection of both spring-fed North Bank tributary-derived water and ponding of Wairau-derived water.

The sole oxygen isotope value collected from Pukaka Drain area was found to be -6.53 ‰ (Figure 5.3), less negative than most other North Bank tributary catchments. With an estimated mean catchment altitude of 470m asl (Table 5.1), the $\delta^{18}\text{O}$ value obtained from Pukaka Drain was found to be consistent with the altitude effect. Kaituna Valley was estimated to have a lower mean catchment altitude (340m asl) and suitably had a less negative average $\delta^{18}\text{O}$ value (-6.40 ‰), underlining the importance the altitude effect for the oxygen isotope composition for the North Bank.

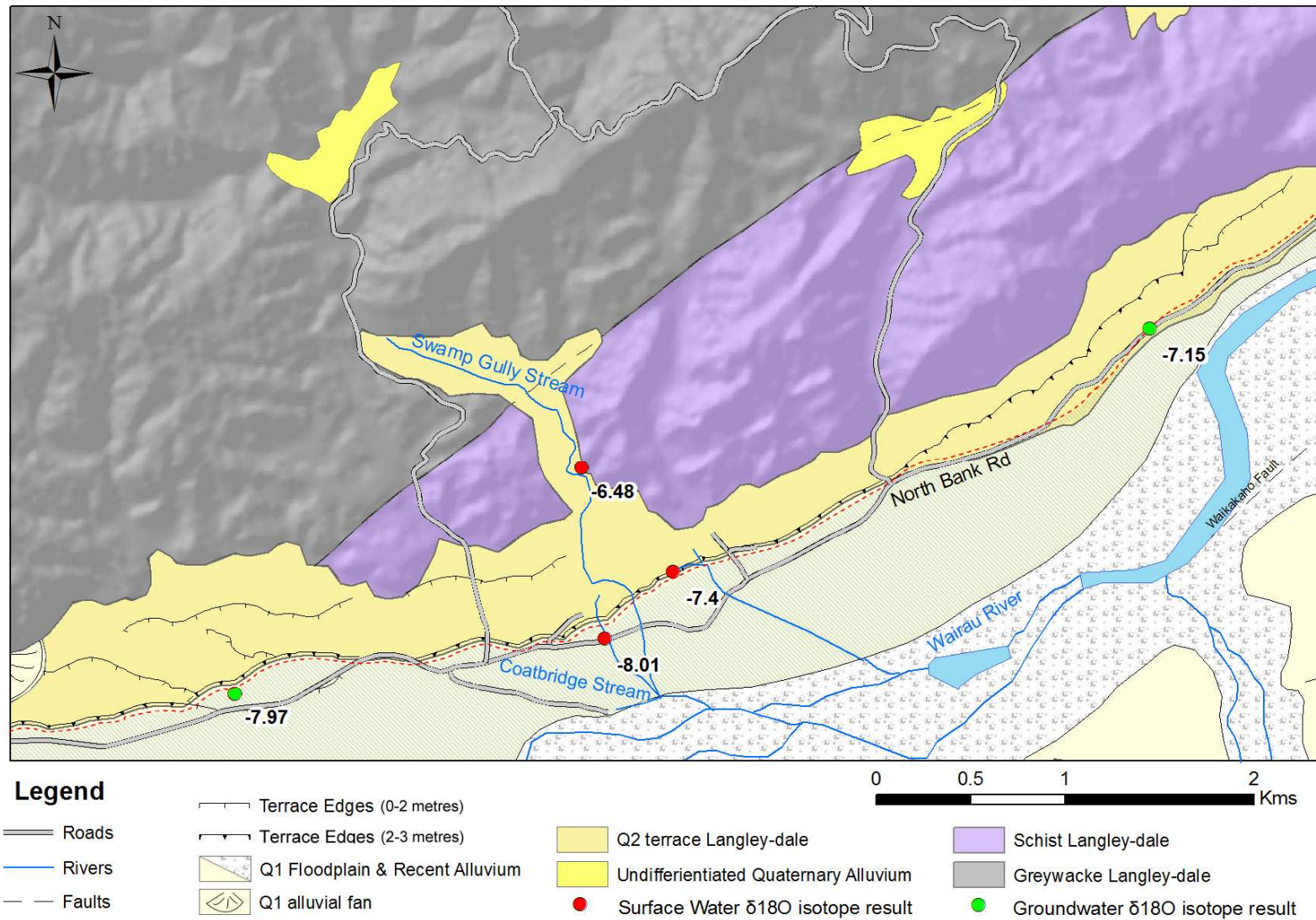


Figure 5.18: Oxygen Isotope value for Coatbridge/Langley-dale in relation to geology and geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River. A mixing zone exists between the red line and the Wairau River.

5.5 CHAPTER SUMMARY

The stable isotope results presented here reveal several important findings:

- 1) Distinct stable isotopic signatures were found between Wairau River waters that come from high mountain catchments versus North Bank waters that arrive more locally at lower altitude.
- 2) The distinction in stable isotope signatures stemmed from the altitude effect, which was found to be the principle factor controlling average $\delta^{18}\text{O}$ values for North Bank catchments rather than distance from the coast.
- 3) The contrast in isotope values allowed identification of water source and detection of potential mixing of Wairau River-derived water with North Bank groundwater. Such mixing of the two types of water suggests a gradational Wairau River-groundwater interface that exists throughout the mixing zone, or, the order of several hundred metres.
- 4) Geomorphology plays a role in limiting the extent of Wairau River influence to either low-lying Q2 Speargrass Formation, Q1 Rapaura Formation alluvium or the Wairau River channel itself. The limit of Wairau River influence is commonly situated at the base of a prominent fluvial terrace scarp present along the majority of the North Bank, and which commonly divides Q2 Speargrass Formation from Q1 Rapuara Formation.

The findings of this study promote use of stable isotopic composition as a forensic tool capable of distinguishing Wairau River water from North Bank tributary groundwater sources. However, due to the major sampling survey only being able to be carried out once, the isotope picture this study portrays is a geochemical snap-shot. Longer-term studies of both precipitation and surface/groundwaters might reveal a different and perhaps more dynamic picture of surface/groundwater interactions on the North Bank of the Wairau River.

Chapter 6

WAIKAKAHO VALLEY

6.1 INTRODUCTION

The Waikakaho Valley is a detailed case study area that is the eastern-most valley in the North Bank study area. Groundwater occurrence, residence time and quantification of through-flow have been sought. Exploratory drilling, pump testing and river stage height recording were conducted in order to examine the relationship between the geology, groundwater and surface water of the valley, the results of which are presented here. Collation of previous geological, hydrogeochemical and hydrogeological studies are also drawn upon to paint a detailed picture of groundwater origin and flow direction within the Waikakaho Valley.

6.2 GEOLOGY

The geology of the Waikakaho Valley is consistent with that broadly outlined for the North Bank study area in Chapter 2 with notable features being its narrow nature and high greywacke schist ranges (Figure 6.1).



Figure 6.1: Looking North, Waikakaho Valley with Waikakaho Road on left. The predominantly-forested greywacke schist slopes form the valley-sides with the same greywacke schist basement at depth. Alluvial infilling of the valley by fluvial deposition has formed flat terraces and floodplains, such as that shown in the foreground.

Basement geology consists mainly of grey, well indurated, well foliated, dominantly pelitic schist, loosely termed greywacke, derived from quartzofeldspathic sandstone and mudstone belonging to the Rakaia Sub-terrane and metamorphosed to greenschist facies (Rattenbury et al., 1998). A large band of Caples Terrane-derived schist traverses the valley in its upper middle reaches and is present again at the valleys head where the Caples/Rakaia boundary occurs (see Geological Map, Figure 2.2). The Caples terrane schist can be described as undifferentiated grey, well foliated, quartz-segregated high grade schist, similarly metamorphosed to greenschist facies. Both rock types thus belong to a zone of regional tectonic metamorphic overprinting, locally referred to as the Marlborough Schist Zone, which has resulted in rocks of a strongly metamorphic nature.



Figure 6.2: a) Weathered greywacke schist outcrop beside Waikakaho Valley Road displaying NE-dipping planes of schistosity b) Close-up of Greywacke schist outcrop.

The valley floor is infilled with a sedimentary sequence of alluvium principally derived from schist material and which has been fluvially deposited in the Quaternary. Thickness of the alluvium is known to vary throughout the valley although is difficult to define due to the lack of wells present. MDC monitoring well 10110 was drilled to 34 metres depth during 4-6 May 2009 without encountering bedrock (and then subsequently pulled back to 12.3m). Nearer the junction of the Waikakaho Valley with the Wairau River, wells P28w/4650 and P28w/2953 were drilled to 19 and 25.4 metres respectively without intercepting bedrock, indicating that reasonable alluvial thicknesses exist in the lower valley. The alluvium is generally expected to be thinner in the upper valley reaches where bedrock is close to the surface, with gradual thickening towards the valley bottom where the flatter valley gradient prompts the river to discharge more of its sediment. The majority of the alluvium within the valley is correlated to the Q2 Speargrass Formation with fluvially-reworked Q1 Rapaura Formation predominant towards the junction of the Waikakaho and Wairau Valleys (see Geological Map, Figure 2.2, back pocket).

Figure 6.3 is a conceptual diagram of the alluvium infilling the Waikakaho Valley that acts as a groundwater aquifer and will be discussed further when regarding hydrogeology. The alluvium can be described as brown, slightly weathered, silty micaceous, orange, grey and white quartz shingle and gravel with varying amounts of clay, although generally minor. Figure 6.4 displays alluvium recovered during the course of drilling well 10110 in May 2009. Alluvium recovered from drilling of a second well 17 metres away, 10109, was very similar with the exception of a 13cm thick clay layer indicative of an overbank clay deposit detected at 11.4 metres depth, highlighting the variability naturally present as a result of fluvial deposition. Geological logging of the material extracted from drilling yielded useful information concerning the similarity of the buried material to that currently being transported by the river.

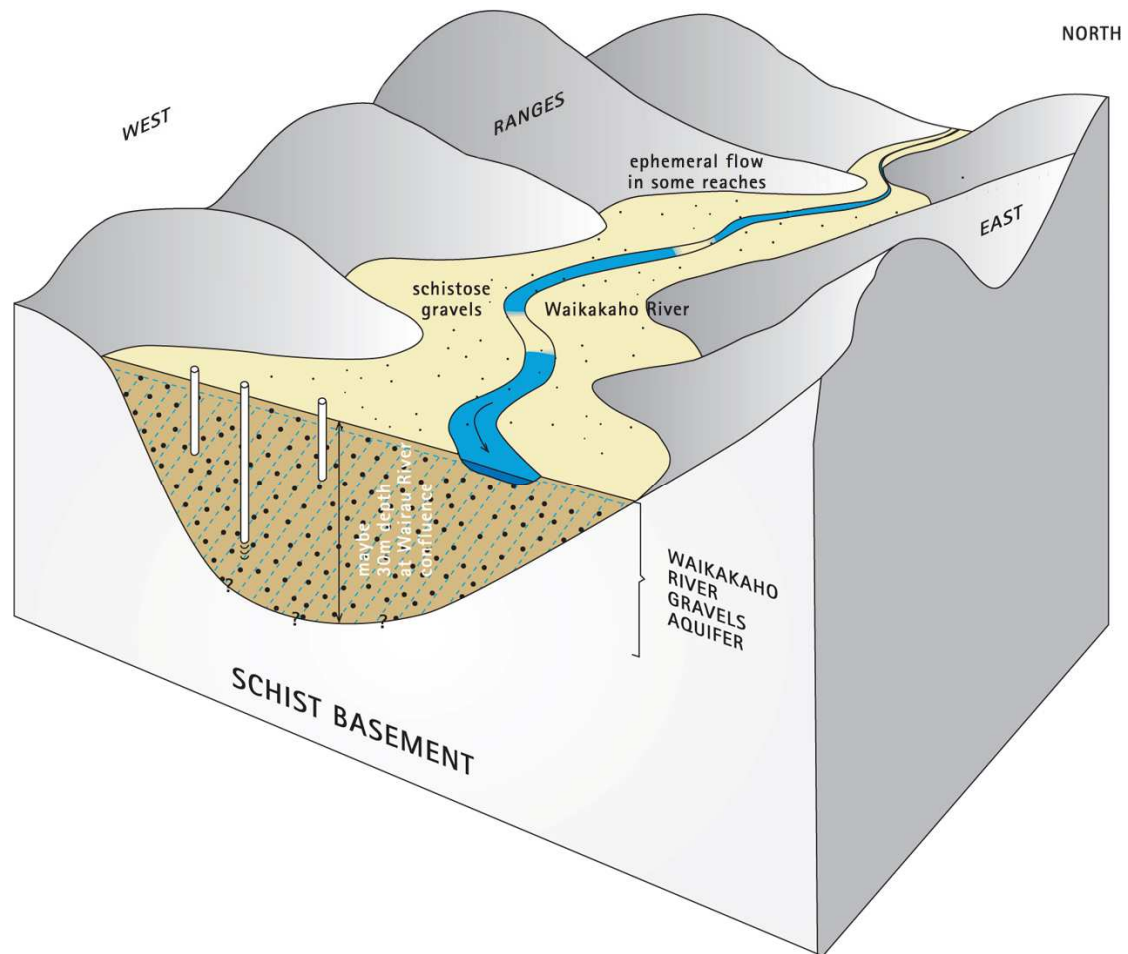


Figure 6.3: Conceptual diagram of the Waikakaho River Gravels Aquifer (Source: P Davidson).

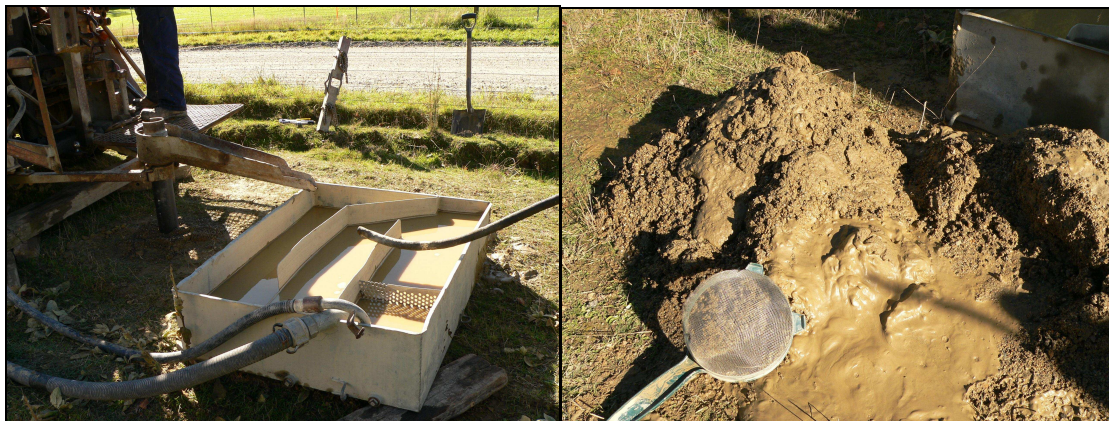


Figure 6.4 Left: Sediment settling box into which sediment was flushed from rotary well drilling 4-6 May 2009. Right: recovered alluvium from rotary well drilling.

The foliations within the schist often cause lines of weakness between the layers of quartz and mica making it prone to soil slip erosion and physical weathering. Consequently, landslide deposits are common across the Waikakaho Valley (see Geological Map). Undifferentiated landslide deposits range from coherent shattered masses of rock to unsorted angular rock fragments in a fine matrix (Begg and Johnston, 2000).

6.3 HYDROGEOLOGY

The hydrogeology of the Waikakaho Valley is characteristic of North Bank tributary valleys with drainage of the Richmond Range by streams and rivers that in turn recharge groundwater within the permeable valley alluvium. The Waikakaho River is the principal river that drains the narrow Waikakaho Valley. While stream flow is often perennial upon the North Bank, the Waikakaho River flows intermittently, particularly in summer months when rainfall is reduced. Ephemeral reaches of the Waikakaho River occur where stream flow becomes groundwater through water entering permeable alluvium. Conversely, channel flow is maintained where impermeable bedrock occurs close to the surface, restricting surface water losses to groundwater. The Waikakaho Valley, having such an interconnected groundwater and surface water resource, has implications for management in that groundwater abstraction may impact upon river stage height in Waikakaho River while, conversely, low flow conditions in the Waikakaho River may impact upon groundwater levels.

It was hypothesised that a seasonal trend may exist where groundwater either migrates to or from the river through the riparian margin. In times of high flow, the Waikakaho River stage height would sit above the groundwater potentiometric surface with a hydraulic gradient between the two, so that surface water contributes to groundwater. In times of low flow within the Waikakaho River, it was hypothesised that the opposite situation would exist where the groundwater potentiometric surface sits above Waikakaho River stage height with a hydraulic gradient towards the Waikakaho River. The potential seasonality of this trend comes about from low flow conditions generally occurring in summer and high flow conditions in winter. The hydraulic connection between the Waikakaho River and groundwater in its riparian margin was examined through water level monitoring and two aquifer pump tests conducted in conjunction with recording river stage height. The methods and results are outlined in subsequent sections.

The hydrostratigraphy of the Waikakaho River Gravels Aquifer was noteworthy when drilling well 10109 for the relative absence of distinct separate aquifer units with only one minor discontinuous clay aquitard layer encountered. Because no such layer was detected when drilling well 10110 seventeen metres away, the aquitard is inferred to be limited in extent. Inspection of well logs available in Waikakaho Valley reveal that clay layers ranging from tens of centimetres to several metres thick are occasionally present in wells, although are similarly inferred to be localised in extent due to their sporadic presence from one well to the next.

The Waikakaho River Gravels Aquifer is broadly classified as an unconfined water-table type aquifer with localised occurrences of yellow-brown clay inferred to be overbank type deposits, consistent with deposition in a fluvial environment. Underlying and flanking the Waikakaho River Gravels Aquifer is impermeable Marlborough Schist that acts as a bedrock aquiclude. The Waikakaho Valley can be assumed as having a single interconnected ground- and surface- water resource, as has been confirmed with the aid of hydrochemistry and stable isotope data (as will be discussed in sections 6.4 and 6.5 respectively). However, while chemical hydrogeology attests to the high degree of hydraulic connection that exists between surface water and groundwater, the physical hydrogeology has yet to be closely examined. The objective and purpose of water level observations and aquifer pump tests carried out by this study in the Waikakaho Valley was to better define the physical hydrogeology.

6.3.1 Water Level Observations

In order to test the relationship between the Waikakaho River and groundwater in its riparian margins, water levels were monitored in both the Waikakaho River and MDC well 10109 seventy metres away, the results of which are presented in Figure 6.5. Data collection began from August 2009 subsequent to installation of a data logger in well 10109 and a stage height recorder in the Waikakaho River (Figure 6.6). The gap in information for MDC well 10109 coincides with the summer aquifer pump test carried out on 28 February 2010. Both groundwater and river levels can be seen to be closely related to one another with an apparent trend of groundwater levels falling below river levels from mid-February onwards. This is likely due to the dry 2010 autumn Marlborough experienced where rainfall-contribution to groundwater was minimal, resulting in a gradual decline in groundwater

levels to below river levels. Increased rainfall mid-May appears to recharge groundwater bringing levels back up to approximate river stage height again.

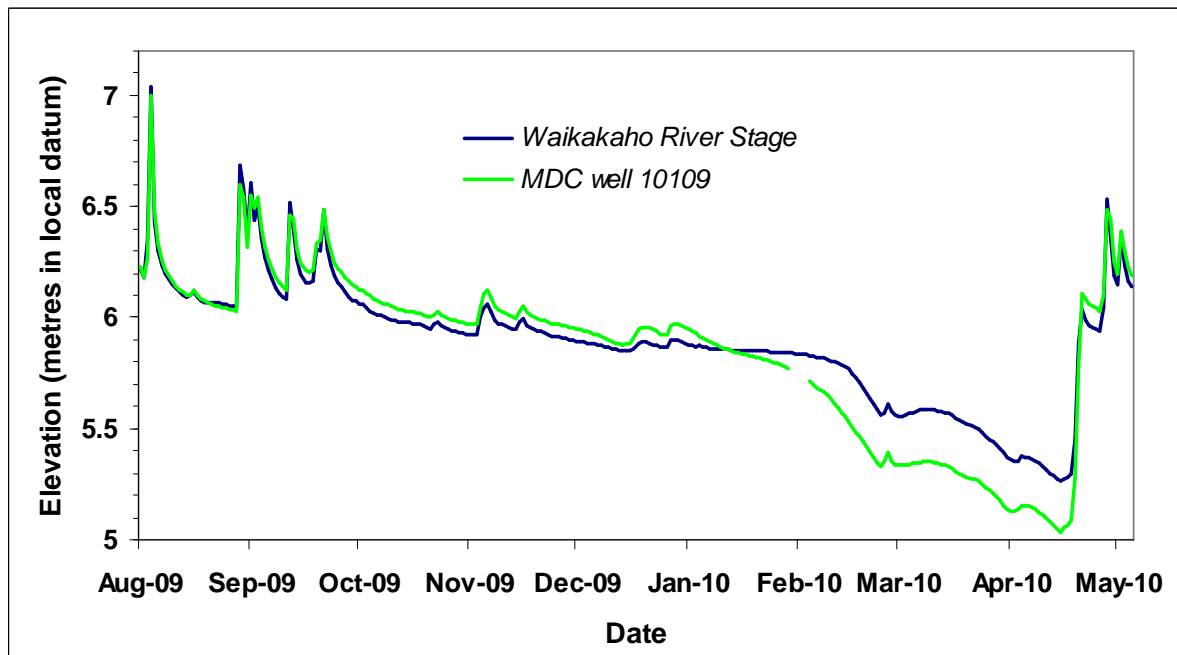


Figure 6.5: Waikakaho River Stage Height vs. MDC Well 10109 groundwater level

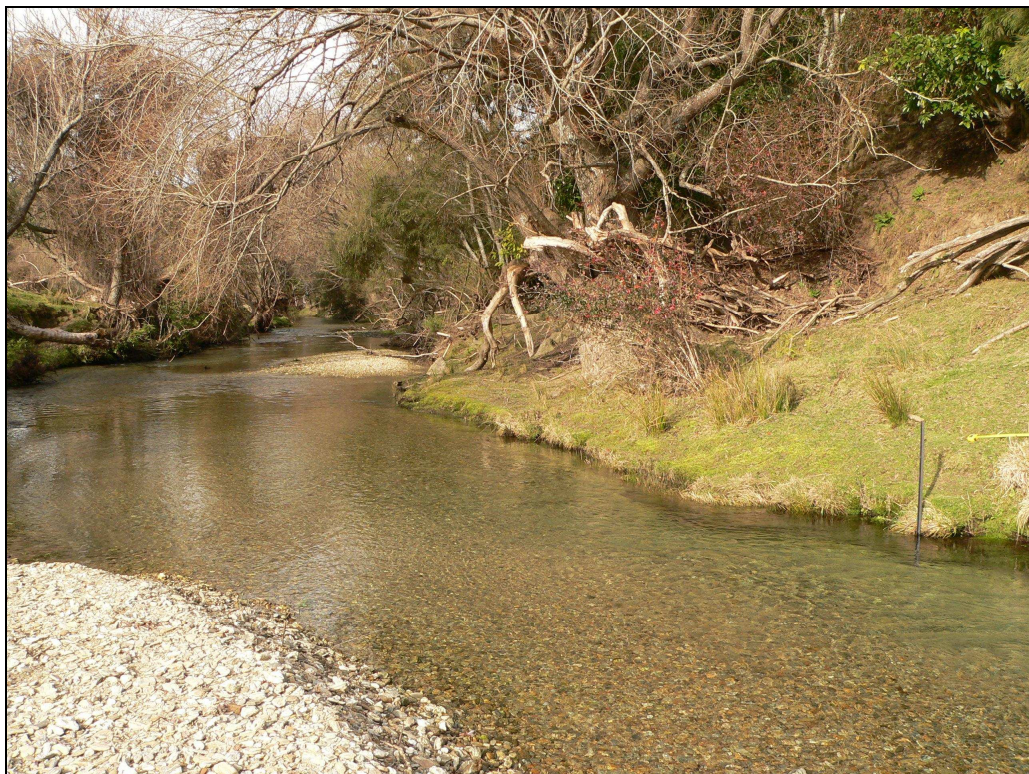


Figure 6.6: Looking South West, Waikakaho River Stage Recording Site, located ~53 metres to west of pumped well 10109. Steel waratah can be seen inserted in river bed on right

6.3.2 Winter Aquifer Pump Test

The relationship between the Waikakaho River and groundwater in its riparian margins was further examined by means of aquifer testing. Aquifer testing consists of pumping a well for a designated time period at a constant rate while drawdown is measured in the pumped well and at least one observation well. The purpose of this test was to be able to calculate aquifer properties of hydraulic transmissivity, conductivity and storativity, along with recording any effect there might be on river stage height in the nearby Waikakaho River. Figure 6.7 illustrates a cone of depression, which is expected to develop shortly after pumping commences and spread radially outwards over time as pumping continues. The rate of movement and shape of the cone of depression depends on several factors, such as aquifer parameters of transmissivity and storativity, the duration and rate of pumping, and the presence of any recharge boundaries that may impact on the extent of the cone of depression. Drawdown in the observation well is a product of the cone of depression from the pumped well intercepting the observation well, thereby causing groundwater levels to fall. As in any aquifer test, drawdown data are critical to the determination of aquifer properties.

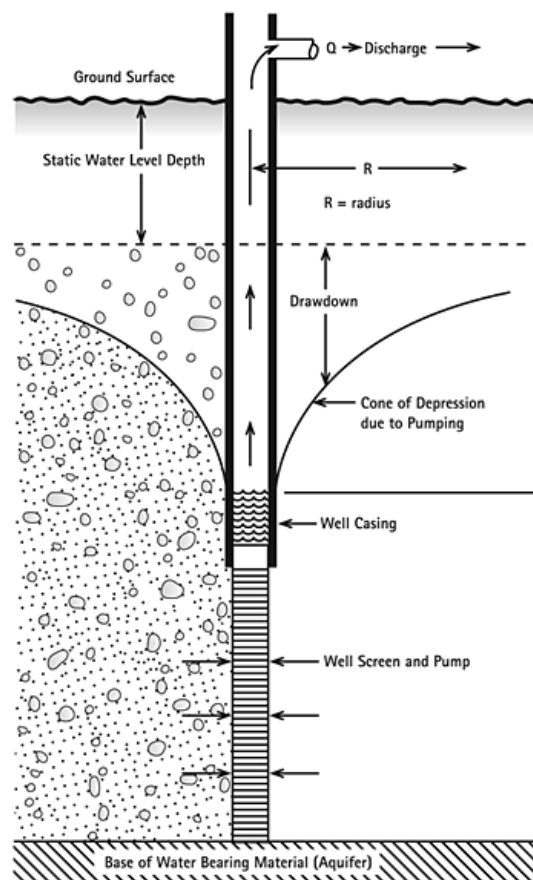


Figure 6.7: Illustration of well terms (Source: P Davidson).



Figure 6.8: Clockwise from top left a) Looking North, location of MDC well 10110 on upper terrace alongside Waikakaho Road. Waikakaho River channel can be seen in middle distance b) Looking East, drilling and location of MDC wells 10110 and 10109, 17m apart on upper terrace, left and right respectively. Photo taken from edge of Waikakaho River Bank c) Observation well 10110 d) Pumped well 10109

Using two MDC exploratory wells drilled in May 2009 (Figure 6.8), an aquifer pump test was conducted on 13 July 2009. Well 10109 (11.46m deep) was pumped at a rate of 475 gpm (29.97 l/s) for a period of 35 minutes while groundwater levels were monitored 17 metres away at Well 10110 (12.3 m deep). The static water level in the pumped well 10109 was -4.185 m. Drawdown data from the pumped well are displayed in Figure 6.9 which was -1.117 m in the first minute of testing, and then reaching and stabilising around -1.142 ± 0.015 m at two minutes and for the remainder of the test. Drawdown stabilisation indicates groundwater recharge was approximately equal to the pumping rate. In this equilibrium situation, the cone of depression stops growing due to reaching a recharge boundary and satisfying steady-state conditions (Fetter, 1994). The static water level in observation well 10110 was -4.122 m with no drawdown recorded for the duration of the test, indicating that the cone of depression from the pumped well did not extend far enough to intercept the observation well. No effect on river stage height in the Waikakaho River was recorded during the test which is reasonable given the added distance (approximately 53 metres) the Waikakaho River is from the pumped well compared to the observation well.

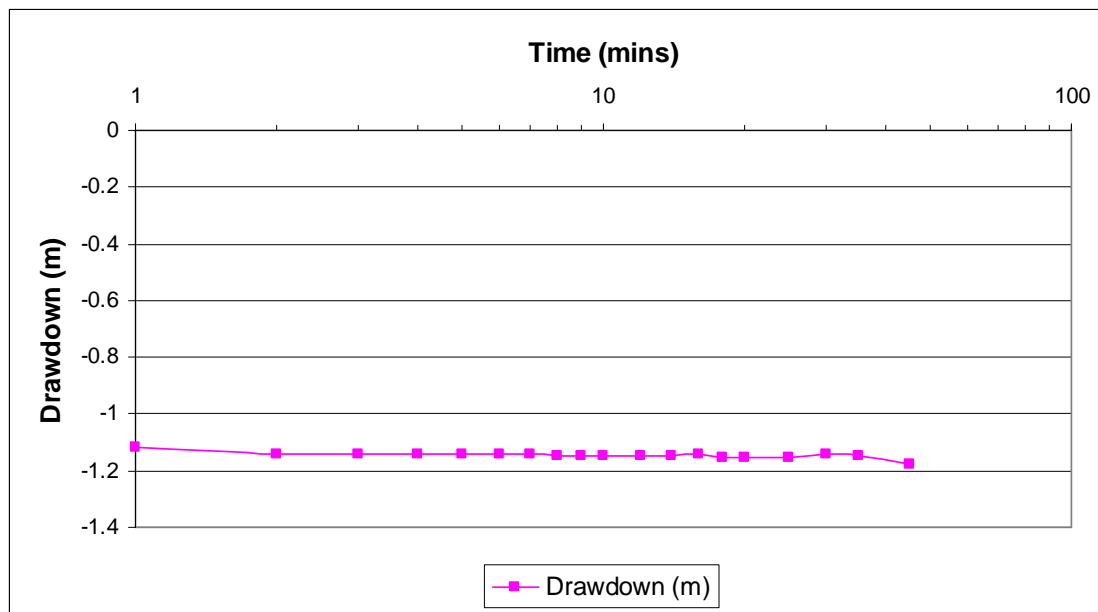


Figure 6.9: Time versus Drawdown for pumped well 10109, winter aquifer test.

The aquifer test was of mixed success as groundwater levels in the observation well 10110 were not able to be lowered through pumping of well 10109. Pumping ceased after 35 minutes as drawdown had not increased in pumped well 10109 for 33 minutes and the cone of drawdown was no longer expected to reach well 10110. Consequently, this prevented calculation of storativity of the aquifer as many analyses, including the Cooper–Jacob analysis, are not applicable to drawdown data that stabilised early from the start of pumping. Instead, an estimate of transmissivity was made from the specific capacity of well 10109 which gave values of 3070 - 2532 m²/day, corresponding to assumed storativity values of 0.03 and 0.3 respectively, common storativity values to assume unconfined aquifers range between (Fetter, 2004). These values signify that well 10109 is a highly productive well with a high transmissivity at that point in the aquifer. Transmissivity values found elsewhere in Waikakaho Valley have a mean ranging from 1267 - 1129 m²/day (Chapter 3), corresponding to assumed storativity values of 0.03 and 0.3 respectively. This indicates that the unconfined Waikakaho Valley gravel aquifer has a low to moderate ability to transmit ground water through its saturated thickness, with transmissivity at well 10109 higher than the Waikakaho average, and an order higher than the approximate representative value for aquifer transmissivity on the North Bank, 455 m²/day.

Despite the relatively high transmissivity at well 10109, no effect on the Waikakaho River was observed which left the question of hydraulic connection between Waikakaho

groundwater and river water unresolved. The pump test did demonstrate, however, that a plentiful groundwater resource exists within the gravels of the Waikakaho Valley due to groundwater recharging the well at approximately the same rate as could be pumped. The source of groundwater recharge, and also the recharge boundary, is inferred to be the Waikakaho River.

6.3.3 Summer Aquifer Pump Test

A repeat aquifer pump test was conducted on February 28th 2010. This test was conducted in summer when both river-flow and groundwater levels were expected to be lower and which represents the critical time where groundwater-users are likely to want to irrigate, potentially having an adverse effect on Waikakaho River levels. The Waikakaho River was estimated to be flowing at less than 50 l/s, below the cut-off threshold of 80 l/s when irrigators would have to stop taking water. Conditions were ideal for repeating the aquifer test to measure groundwater through flow under typical summer low flows.

Using the same wells as in July 2009, Well 10109 (11.46 m deep) was pumped at a rate of 450 gpm (28.39 l/s) for a period of 210 minutes while groundwater levels were monitored 17 metres away at Well 10110 (12.3 m deep). The extended pumping time was to ensure that any potential hydraulic effects that could occur in summertime, where both river flow and groundwater levels are reduced, would be observed. Due to the lower expected transmissivity at this time of year it was anticipated that a fall in groundwater levels at the observation well could be induced in order to calculate aquifer storage. The static water level in the pumped well 10109 was -4.259 m, some 7.4 cm lower than in the winter test. Drawdown data from the pumped well are displayed in Figure 6.10 which was -1.118 m in the first minute of testing, decreasing slightly to -1.112 m at two minutes, and then gradually increasing from 1.112 m to a maximum of -1.166 at the cessation of pumping at 210 minutes. The very gradual increase in drawdown suggests that the pumping rate slightly outweighed groundwater recharge with 210 minutes of pumping inducing a modest drawdown of 5.4 cm in the pumped well, approaching near steady-state conditions. The static water level in observation well 10110 was -4.497 m and no drawdown was recorded over the duration of the test, indicating that the cone of depression from the pumped well did not extend far enough to intercept the observation well. Likewise, no effect on river stage height in the Waikakaho River was recorded during the test.

Like the winter pump test, groundwater levels in the observation well could not be lowered through pumping of the pumped well, again, preventing calculation of aquifer storativity. Estimation of transmissivity was made using the specific capacity of the pumped well which gave values of 2396 - 1980 m²/day, corresponding to assumed storativity values of 0.03 and 0.3 respectively. These transmissivity values were lower than those found during the winter aquifer pump test, however, as transmissivity calculations are based on specific capacity which is a function of pump rate, the slightly lower pump rate for the summer test (2589 m³/day versus 2453 m³/day) may play a minor role in the lower transmissivities calculated. These transmissivity values at well 10109 were again higher than the Waikakaho average with summer groundwater recharge appearing sufficient to prevent potential interference between these wells 17 metres apart. Levels in the Waikakaho River did not change throughout the test which supports that either the groundwater resource is sufficient for no effect on river stage height to be observed or that there is limited hydraulic connection between well and river. From water level observations (6.3.1), groundwater and river levels appear to be closely related to one another, and a similar hydrogeochemistry (as discussed in 6.4), both promote a plentiful groundwater resource as the favoured explanation. Overall, the pump test demonstrated that a plentiful groundwater resource exists within the gravels of the Waikakaho Valley, even at a critical time where groundwater-users are likely to want to irrigate, potentially having an adverse effect on already low Waikakaho River levels.

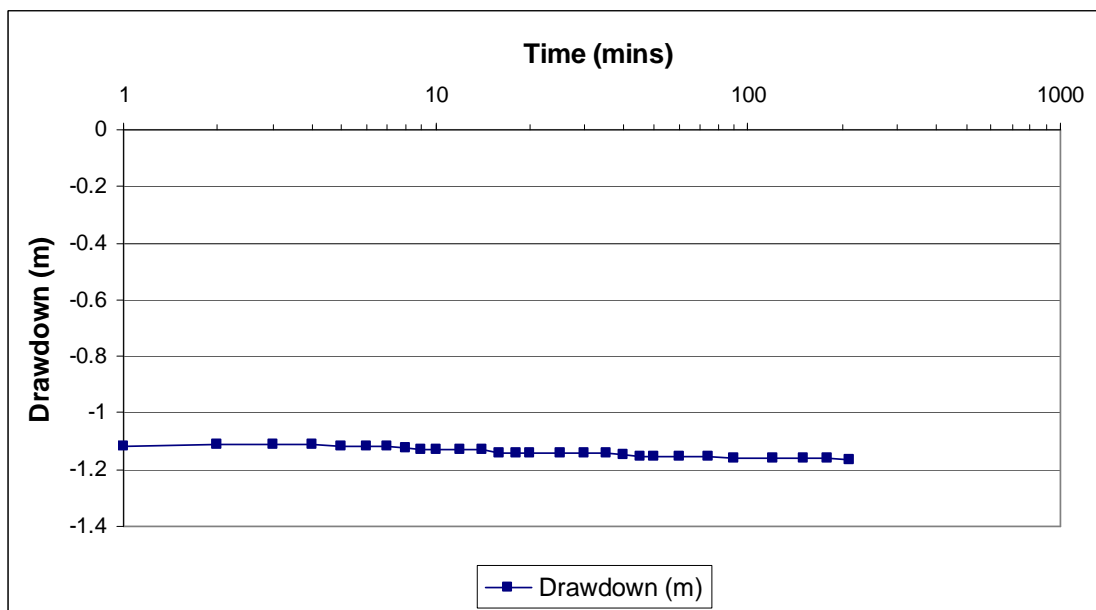


Figure 6.10: Time versus Drawdown for pumped well 10109, summer aquifer test.

6.4 HYDROGEOCHEMISTRY

The hydrogeochemistry of Waikakaho Valley was examined as part of the sampling survey carried out 3-6 August, 2009, with the exception of two sample sites (site 034 well 10109 and site 035 Waikakaho River Upstream Wratts Stream) where samples were taken twice, both during the course of an aquifer test. The hydrogeochemistry of Waikakaho Valley was found to be consistent with other North Bank tributary valleys although a slightly higher level of iron was detected in both groundwater and surface water.

The North Bank was found to have an average iron content of 0.024 mg/l (excluding the two samples that had greater than 0.1 mg/L which were deemed to be collecting soluble iron from well casings). The average iron content for the Waikakaho Valley was slightly higher at 0.036 mg/L. Similar to the Onamalutu River, iron content within the waters of the Waikakaho River increased in a downstream direction (Table 6.1).

Table 6.1: Waikakaho Valley iron concentrations measured 3-6 August, 2009, with the exception of two sample sites (site 034 well 10109 and site 035 Waikakaho River Upstream Wratts Stream) where samples were taken twice, both during the course of an aquifer test

Site	Iron concentration (mg/L)	Dissolved Oxygen (mg/L and % saturation)
017 Waikakaho River Bridge Rocky Creek	0.005	11.28 (95.2 %)
035 Waikakaho River Upstream Wratts Stream	0.05	10.24 (88%)
015 Waikakaho Road Bridge	0.05	9.8 (88.2 %)

A survey carried out by MDC 29 November 2007 mirrored this trend of iron concentration increasing slightly in a downstream direction with an iron concentration of 0.003 mg/L measured at Waikakaho River Bridge Rocky Creek increasing to 0.022 mg/L measured at Waikakaho Road Bridge (MDC, 2008). The slight increase in iron concentration in a downstream direction is in keeping with the gradual reduction of dissolved oxygen in both groundwater and surface water allowing greater iron solubility and concentration. This may be due in part to lessening of both the valley gradient and hydraulic gradient, leading to slower surface water and groundwater flow velocities. Nevertheless, iron concentrations

within Waikakaho Valley are still comparatively low, which is consistent with the dilute anoxic nature of the waters of the North Bank.

Stiff plots for the Waikakaho Valley are shown in Figure 6.11 and all display a similar chemical signature with the exception of site 016 Well 10100. There, a relatively high concentration of dissolved solids was encountered (TDS = 106.4 mg/L) with elevated sodium and chloride (16 mg/L and 24 mg/L respectively). While still relatively dilute, these elevated sodium and chloride concentrations are double those measured at most Waikakaho sampling sites and could potentially indicate an influence by agricultural chemicals and/or a longer groundwater residence time. With TDS content similarly high at site 014 Well P28w/4650 (101.8 mg/L) where groundwater residence time is inferred to be around 1 year (MDC, 2008) and yet lower sodium and chloride concentrations exist (10 mg/L and 14 mg/L), an agricultural chemical influence is the favoured explanation for elevated sodium and chloride concentrations at Well 10100.

Generally, well water and river water are chemically indistinguishable with simultaneous trends of TDS content increasing in a downstream direction and groundwater having a slightly higher level of TDS than surface water. Table 6.2 displays TDS content of surface water and groundwater within Waikakaho Valley from multiple sampling surveys. It can be seen that groundwater tends to have a slightly higher level of dissolved salts than surface water for a given sampling survey illustrating that it is more evolved than channel water. This is probably a reflection of longer residence time and further water-rock interaction.

Waikakaho Valley Stiff plots

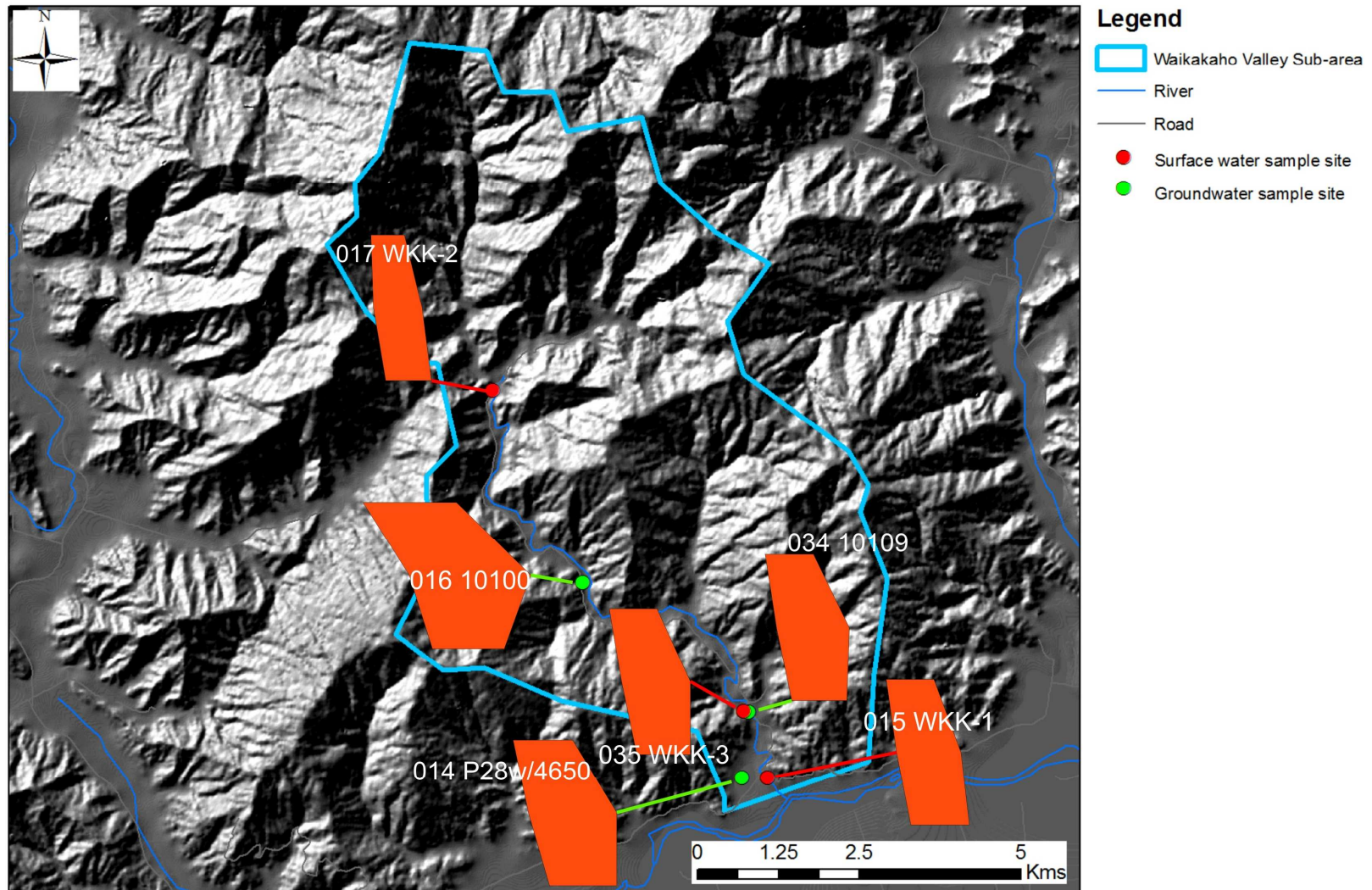


Figure 6.11: Stiff plots for Waikakaho Valley August 3rd-6th 2009 (site 034 and 035 collected July 13th).

Table 6.2: Comparison of TDS content for surface water and groundwater within Waikakaho Valley from sampling surveys carried out 29 November 2007 (MDC, 2008) and by this study 13 July 2009 and 28 February 2010. Red indicates surface water while green signifies groundwater.

Site	29 November 2007	13 July 2009	28 February 2010
017 Waikakaho River Bridge Rocky Creek	63.05	54.25	-
035 Waikakaho River Upstream Wratts Stream	-	66.92	60.66
034 MDC well 10109	-	69.85	59.66
014 Tyson well P28w/4650	97.82	85.22	-
015 Waikakaho Road Bridge	79.33	69.29	-

6.5 STABLE ISOTOPES

Stable isotope results are presented in Figure 6.12. The water samples were collected as part of the sampling survey carried out 3 to 6 August 2009 except for two samples which were collected on 13 July during the winter pump test. The average $\delta^{18}\text{O}$ value found for Waikakaho Valley was -6.47 ‰ with all values within ± 0.35 ‰ of this mean value, signifying that the time separation between sampling on 13 July and on the 4 August had only a minor effect on $\delta^{18}\text{O}$ composition. As all $\delta^{18}\text{O}$ values fell between a range of -6 ‰ to -7 ‰, local rainfall recharge is attributed as the source for both surface water and groundwater within the Waikakaho Valley catchment. A previous study by MDC (2008) included oxygen isotope sampling as part of its survey, the results of which are shown in Table 6.3. The $\delta^{18}\text{O}$ values are similar to those found by this study and, when taking the natural temporal variability in $\delta^{18}\text{O}$ in groundwater and surface water into account, suggest $\delta^{18}\text{O}$ values within the Waikakaho Valley are relatively consistent. Table 6.3 also displays the $\delta^{18}\text{O}$ values collected 28 February 2010 which again demonstrate that $\delta^{18}\text{O}$ values within the Waikakaho Valley are relatively consistent, with a maximum separation of 0.35 ‰ found between winter and summer measurements respectively.

Waikakaho Valley Oxygen Isotope Results

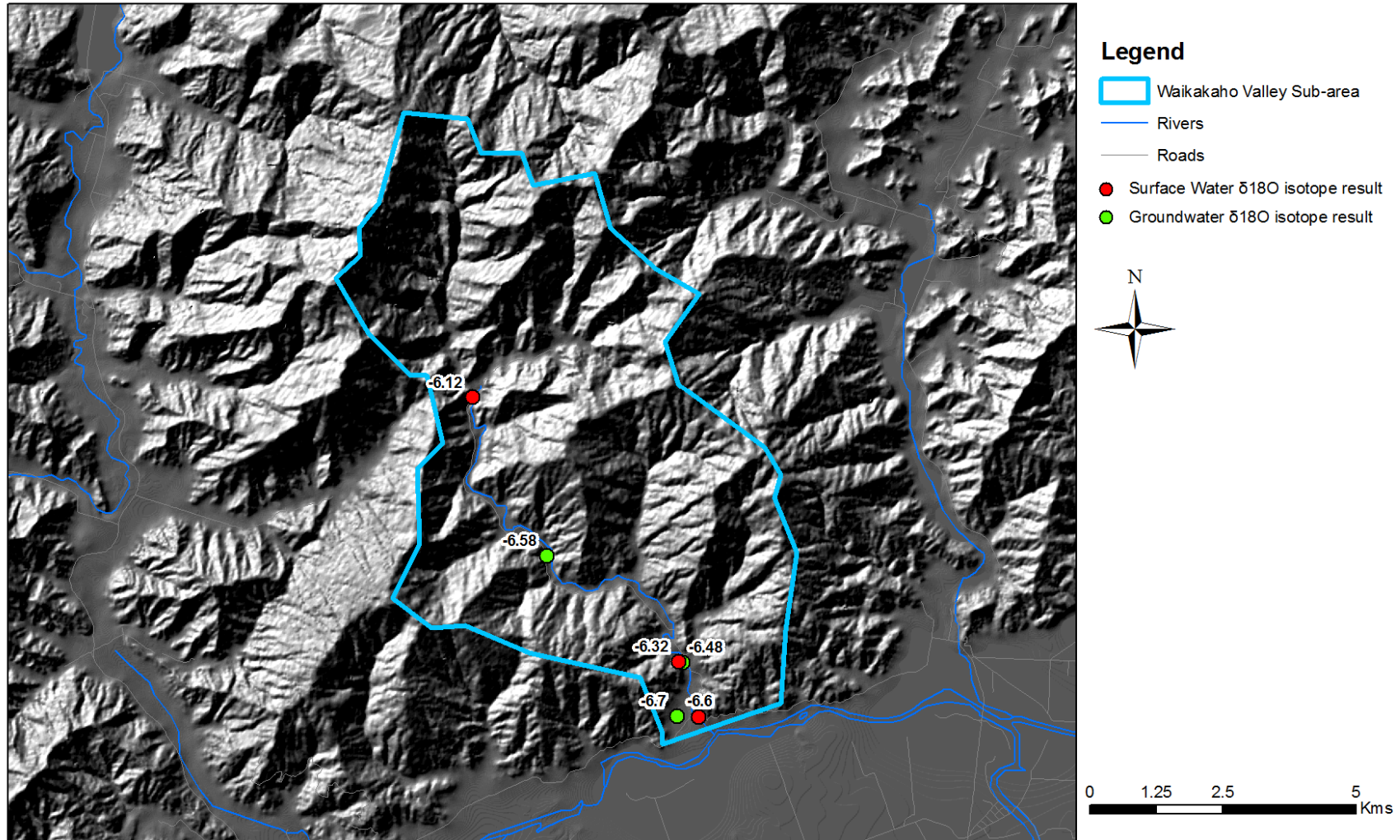


Figure 6.12: Oxygen Isotope results for Waikakaho Valley August 3rd-6th 2009 (site 034 and 035 collected July 13th). Results are in units $\delta^{18}\text{O}$ ‰ compared to V-SMOW

Table 6.3: Comparison of $\delta^{18}\text{O}$ values within Waikakaho Valley from multiple sampling surveys.

Site	29 November 2007	13 July 2009	28 February 2010
017 Waikakaho River Bridge Rocky Creek	-6.38	-6.12 ‰	-
035 Waikakaho River Upstream Wratts Stream	-	-6.32 ‰	-6.67 ‰
034 MDC well 10109	-	-6.48 ‰	-6.66 ‰
014 Tyson well P28w/4650	-6.50 ‰	-6.70 ‰	-
015 Waikakaho Road Bridge	-6.46 ‰	-6.60 ‰	-

High altitude sourced water, such as that of from the Wairau River, gives a significantly more negative $\delta^{18}\text{O}$ value (circa -8.5 ‰) than that found in tributary valleys and it is on that basis that Wairau River-influence is deemed to be limited close to its own channel, as seen in Figure 6.13. Close to the Waikakaho River/Wairau River confluence, groundwater from the Q2 Speargrass Formation was -6.7 ‰ signifying that the Wairau River does not influence groundwater within these gravels. At lower elevation, the Waikakaho River Q1 floodplain is thought to be dominated by Waikakaho-derived waters (-6.6 ‰ at Waikakaho Road Bridge) thus limiting the influence of Wairau River-derived waters to its own channel. It is possible that Wairau influence may extend into Q1 Rapaura Formation gravels at the bottom of Waikakaho Valley, although the geomorphic boundary of a minor terrace and the proximity of the nearby and presumably groundwater-recharging Waikakaho River make this unlikely.

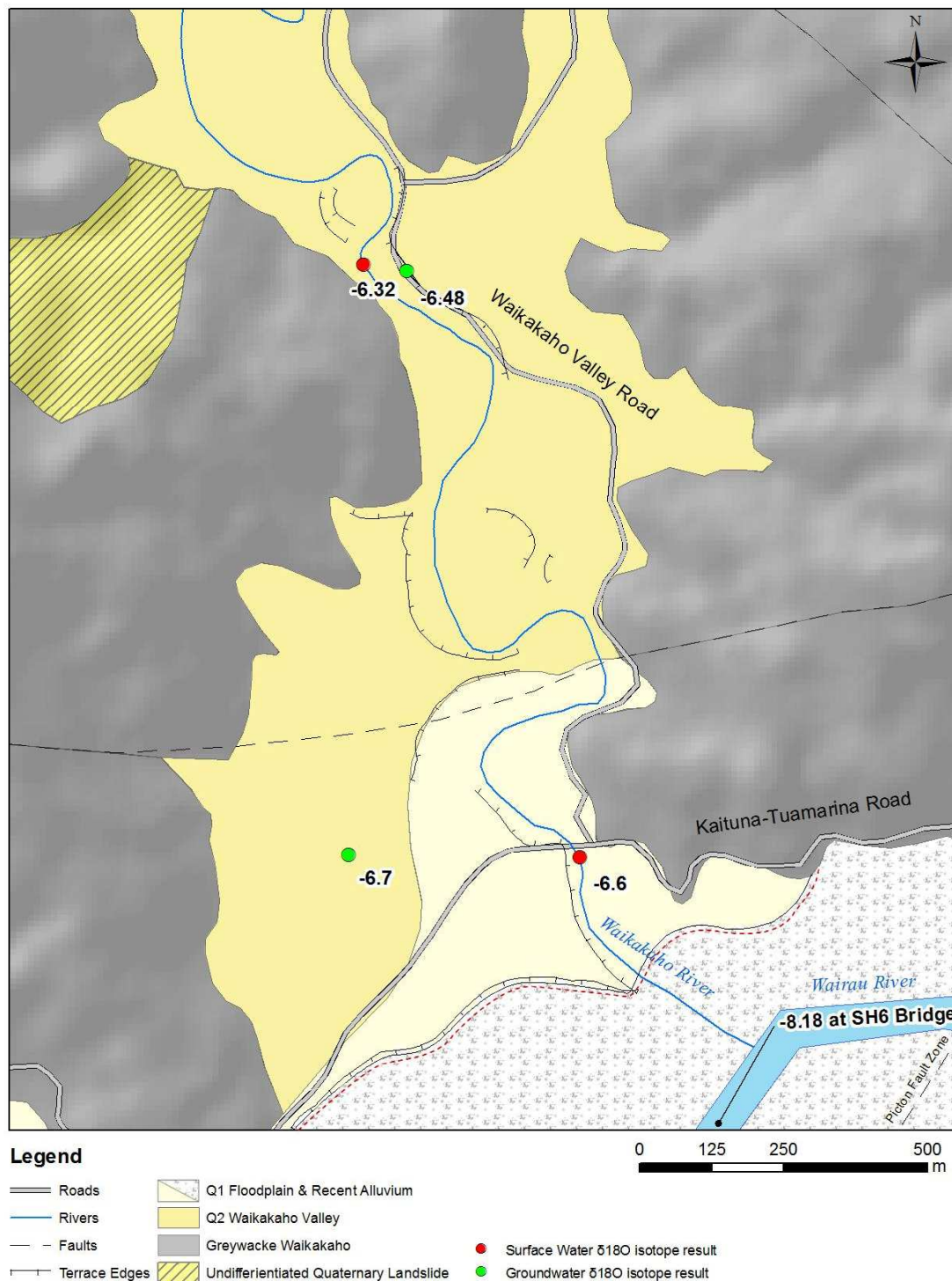


Figure 6.13: Oxygen isotope values at junction of Waikakaho Valley and Wairau River in relation to geology and geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River.

6.6 LINKWATER STUDY

A groundwater study by GNS Science conducted in Linkwater provides a point of comparison to the Waikakaho Valley. Situated to the north of Waikakaho Valley and separated from Waikakaho Valley by the Richmond Range, Linkwater is a low-lying 5 km long alluvial plain between Okiwa Bay at the head of Queen Charlotte Sound to the east, and the Mahakipawa Arm of Pelorus Sound to the west (Figure 6.14). Groundwater oxygen isotope values were found to be less negative with an average $\delta^{18}\text{O}$ value of -6.17 ‰ (Morgenstern et al., 2009) compared to the Waikakaho Valley average of -6.47 ‰. Groundwater recharge is inferred to be principally from low-altitude rainfall, predominantly sourced from water vapour from Tasman Bay to the North West. The less negative $\delta^{18}\text{O}$ values measured at Linkwater are likely due to the altitude effect with Linkwater mean catchment altitude lower than that of the Waikakaho catchment (estimated mean catchment altitude is 440m asl for Linkwater compared to 480m asl for Waikakaho Valley). Similar to Waikakaho Valley, oceanic water vapour from Tasman Bay must travel over several mountain ranges (namely the Bryant and Bull Ranges west to east respectively) with the altitude effect lowering $\delta^{18}\text{O}$ values to around -6.17 ‰ for subsequent rainfall at Linkwater.



Figure 6.14: Linkwater Catchment (Morgenstern et al., 2009).

The hydrogeochemistry of the Linkwater catchment is similarly dilute in regard to dissolved solids, consistent with relatively young groundwater derived from rainfall.

6.7 CHAPTER SUMMARY

The geology of the Waikakaho Valley is befitting of its North Bank setting with basement geology consisting of rock types of a strongly metamorphic nature, collectively termed Marlborough Schist. The principle rock type is a grey, dominantly pelitic schist, belonging to the Rakaia Sub-terrane and loosely termed greywacke. The secondary rock type present in the upper middle reaches and valley head is an undifferentiated grey, well foliated, quartz segregated high grade schist belonging to the Caples Terrane.

The valley floor has an alluvium infilling generally expected to be thinner in the upper valley reaches where bedrock is close to the surface, and thicker towards the valley bottom where the flatter valley gradient prompts the river to discharge more of its sediment. The majority of the alluvium within the valley is correlated to the Q2 Speargrass Formation.

The hydrogeology of the Waikakaho Valley is characteristic of the North Bank with drainage of the Richmond Range by streams and rivers that in turn recharge groundwater within the permeable valley alluvium. The Waikakaho Valley, having such an interconnected groundwater and surface water resource, was hypothesised to have seasonal trend where groundwater either migrates to or from the river through the riparian margin. This was examined through water level observations of the Waikakaho River and an observation well, along with two aquifer pump tests carried out in winter and summer respectively.

Water level observations revealed that water levels in the Waikakaho River and well 10109 were closely related over a nine month timeframe. The aquifer tests were of mixed success as groundwater levels in the observation well 10110 were not able to be lowered through pumping of well 10109 preventing calculation hydraulic parameters such as storativity. The aquifer pump tests did demonstrate, however, through groundwater recharging the well equal to the pump rate, that a plentiful groundwater resource exists within the gravels of the Waikakaho Valley, even at a critical time where Waikakaho River levels are low. No effect on Waikakaho River stage height was observed during pumping further highlighting the abundance of the groundwater resource.

The hydrogeochemistry of Waikakaho Valley was found to be consistent with other North Bank tributary valleys with surface water and groundwater chemically indistinguishable from one another. Groundwater tended to have a slightly higher level of TDS than surface water, a function of longer residence time and further water-rock interaction by groundwater than surface water. The hydrogeochemistry of Waikakaho Valley was also found to be chemically indistinguishable from Wairau River water, likely due to the dilute nature of both types of water.

Stable isotope values for $\delta^{18}\text{O}$ ranged between -6 ‰ to -7 ‰ indicating low-altitude and local rainfall as the source of recharge for both surface water and groundwater within the Waikakaho Valley catchment. Stable oxygen isotope values within the Waikakaho Valley catchment were found to be relatively consistent across multiple sampling surveys and multiple studies. Wairau River-influence upon groundwater is deemed to be limited close to its own channel based on its significantly more negative $\delta^{18}\text{O}$ signature. Wairau River waters were not detected, even close to the Waikakaho River/Wairau River confluence, suggesting groundwater flow rates from Waikakaho Valley are sufficient to limit Wairau River-influence and/or there is limited hydraulic connection.

In the Linkwater Catchment to the north of Waikakaho Valley, it was established that an average $\delta^{18}\text{O}$ value of -6.17 ‰ (Morgenstern et al., 2009) is comparable although slightly more negative than the Waikakaho Valley average of -6.47 ‰. This is attributed to the altitude effect with otherwise similarly dilute waters consistent with relatively young groundwater derived from rainfall.

Chapter 7

TOP VALLEY, TIMMS CREEK AND CAT CREEK

7.1 INTRODUCTION

The grouping of Top Valley, Timms Creek and Cat Creek comprise a detailed case study area that form the westernmost valleys in the North Bank study area. Similar to elsewhere on the North Bank, the extent of the Wairau River-groundwater interface has been sought to be constrained, along with groundwater flow directions. This was achieved primarily through hydrogeochemical and stable isotope analysis, and also through incorporating geological and geomorphic mapping to examine the relationship between the geology, groundwater and surface water of the valley. Collation of previous geological studies are also drawn upon to paint an integrated picture of groundwater origin and flow direction within the Top Valley, Timms Creek and Cat Creek area.

7.2 GEOLOGY

The geology of the Top Valley, Timms Creek and Cat Creek is consistent with that broadly outlined for the North Bank study area in Chapter 2 with notable features being schist ranges of Caples terrane-affinity forming the majority of the catchment headwaters while Rakaia sub-terrane greywacke schist predominates the lower valley areas (see Geological Map, Figure 2.2). Of particular significance to hydrogeology are prominent fluvial terraces present in all three valleys (Figure 7.10, Figure 7.11 and Figure 7.12) which serve to separate Q2 Speargrass Formation alluvium from Q1 Rapaura Formation alluvium.

Rock basement consists of rock types belonging to a zone of regional tectonic metamorphic overprinting, locally referred to as the Marlborough Schist Zone. As aforementioned, these rock types are Caples terrane schist and Rakaia sub-terrane greywacke, and are rocks of a strongly metamorphic nature. Historic gold prospecting concentrating on the Timms Creek and Top Valley areas was carried out by Tronoh Mining Limited in 1937 and 1938. A combination of seismic surveying and drilling techniques were used to determine the depth to bedrock. The lines along which drilling was carried out are presented in Figure 7.1 with accompanying cross sections in Figure 7.2. The cross sections indicate that depth to bedrock varies with restricted

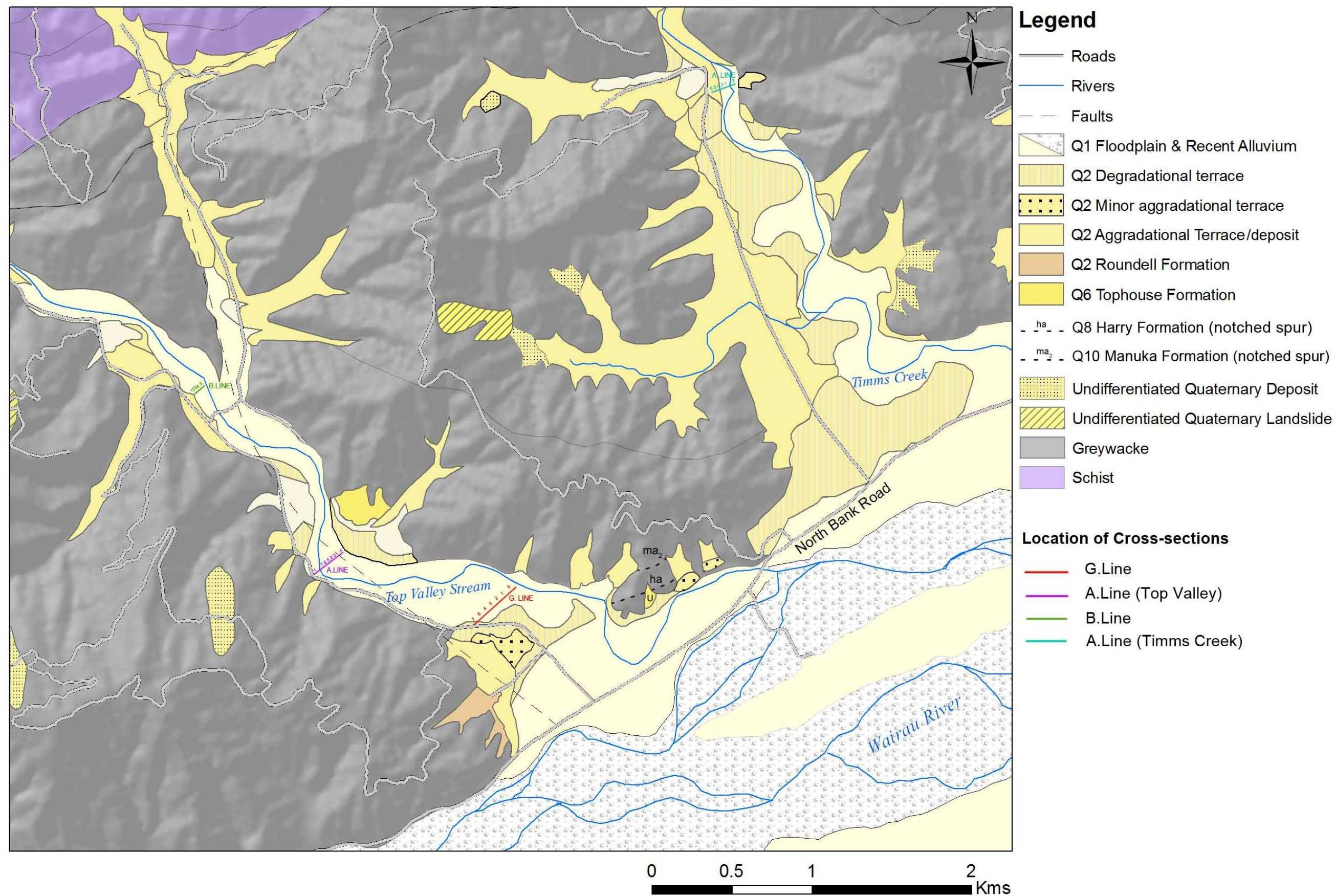


Figure 7.1: Geological base map displaying the major lines along which drilling was carried out, 1937 and 1938, by Tronoh Mining Ltd. Borehole numbers and location along lines are as shown.

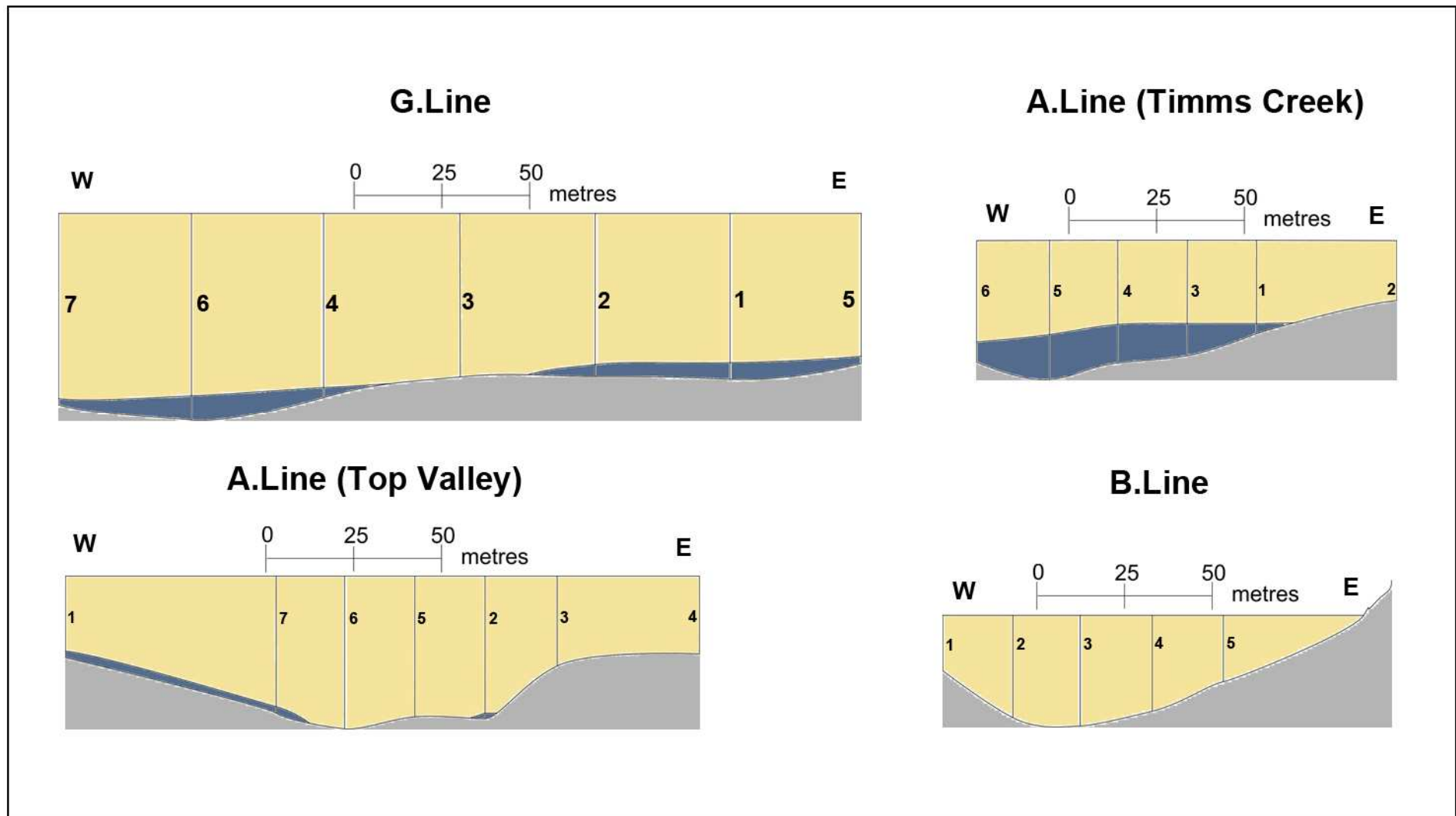


Figure 7.2: Cross sections from Top Valley and Timms Creek. Grey indicates bedrock, blue signifies a blue clayey gravel (or "blue wash" as described in Timms Creek), while pale yellow represents yellow fine to medium gravel. Boreholes are numbered as drilled.

and narrow bedrock channels in the higher reaches of the valley and flatter bedrock surfaces towards the valley bottoms. Line B in particular shows an incised bedrock channel that suggests intense scouring took place when the valley was formed while Line G demonstrates a much broader and flatter bedrock surface upon which more expansive alluvial deposition took place.

Overlying rock basement is an alluvial infilling that forms the valley floors in Top Valley, Timms Creek and Cat Creek. In Figure 7.2, the depth of alluvial infilling can be seen to vary throughout the valley although typically approaches c. 50 metres in the deepest valley incision in each cross section. Like the Waikakaho Valley, the alluvium is principally derived from schist material which has been fluvially deposited during the Quaternary. The alluvium is generally expected to be thinner in the upper valley reaches where bedrock is close to the surface, with gradual thickening towards the valley bottom where the flatter valley gradient prompts the river to discharge more of its sediment. Driller descriptions of the alluvium describe a yellow fine to medium gravel with little clay, fairly uniform in composition and free from clay or cement layers. The majority of the alluvium is correlated to the Q2 Speargrass Formation with post glacial Q1 Rapuara Formation gravels adjacent to modern river channels. A blue clayey-gravel recorded at depth is inferred to correspond to either early Speargrass Formation or an older outwash deposit subsequently modified by deposition of Speargrass alluvium. The alluvium in its entirety is broadly regarded as a groundwater aquifer and will be discussed further in relation to hydrogeology.

7.3 HYDROGEOLOGY AND FLOW DIRECTIONS

The hydrogeology of the Top Valley, Timms Creek and Cat Creek area is characteristic of North Bank tributary valleys with drainage of the Richmond Range by streams and rivers that in turn recharge groundwater within the permeable valley alluvium. There are few wells in the Top Valley, Timms Creek and Cat Creek area due to the reliance on perennially flowing rivers and streams, and the low demand from the lower density of settlement and high average rainfall the area receives. Consequently, there is little lithologic information relating to subsurface deposits, with the exception of historic gold-prospecting borelogs that detail a significant thickness of fairly uniform alluvium overlying bedrock. The alluvium infilling the valleys is broadly regarded as an unconfined water-table type aquifer with no major confining clay layers to act as aquitards, as can be seen in the conceptual cross section

in Figure 7.3. Underlying and flanking the unconfined aquifer is relatively impermeable Marlborough Schist that essentially acts as a bedrock aquiclude. The unconfined aquifer is assumed to receive groundwater recharge via rainfall infiltration and from streams and rivers that drain the Richmond Range. The unconfined aquifer acts as a reservoir that conveys groundwater down valley, both giving and receiving water to and from streams and rivers. Permeability is expected to be greatest closest to present day streams and rivers where fluvial reworking of sediment has resulted in alluvium of higher hydraulic conductivity and transmissivity (Rapaura Formation). As such, the unsaturated zone may be greater in Speargrass Formation deposits further away from North Bank tributaries, where permeability is lower.

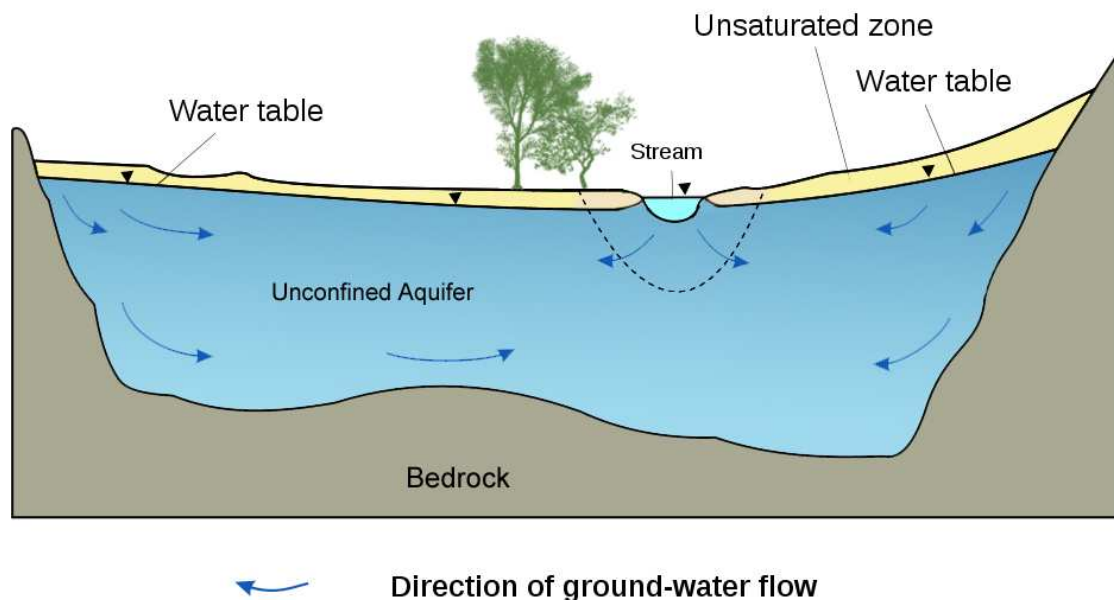


Figure 7.3: Conceptual cross section of unconfined groundwater aquifer thought to exist in incised valleys of Top Valley, Timms Creek and Cat Creek. Cat Creek flows ephemeral as a result of channel water being lost to groundwater for much of the year.

Closer to their junction with the Wairau River, groundwater flow directions for the Timms Creek and Cat Creek area have been estimated as part of a piezometric contouring exercise carried out by Pattle Delamore Partners (PDP), 2009. As seen in Figure 7.4, a network of 12 piezometers (small-diameter observation wells) were installed in the Timms Creek and Cat Creek area and used to measure the hydraulic head at each well point. Where a head differential existed between two points, a hydraulic gradient could be determined, from which groundwater flow directions can be deduced. As Figure 7.4 shows, the net movement of groundwater creates a broad arcuate shape upon the North Bank with groundwater flow directions inferred to be perpendicular to piezometric contours.

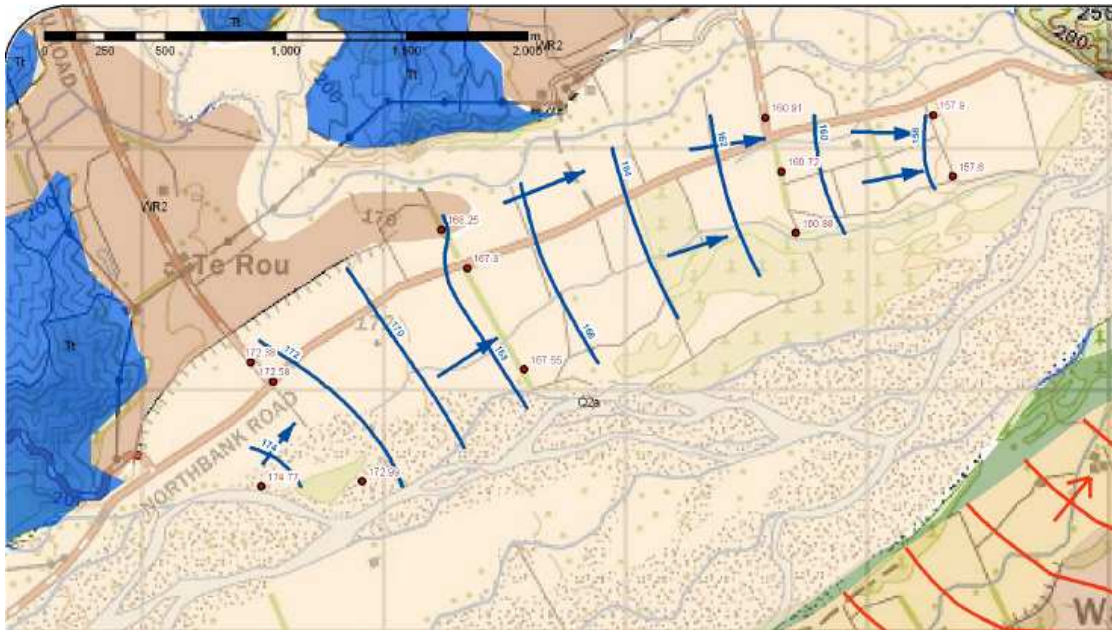


Figure 7.4: Groundwater Contours with general indication of groundwater flow direction, Timms Creek (Source: P Callender, 2009).

Groundwater movement in a broad sweep such as this implies Wairau-derived groundwater enters the North Bank upstream to the west, travels downstream through the bank and surface water channels before discharging, ultimately, into the Wairau River to the east. The extent of groundwater flow from the Wairau River appears to be constrained geomorphically by a relatively prominent Q2 degradational terrace (illustrated in Figure 7.11 and photographed in Figure 7.5 and Figure 7.6). Further east, a hydraulic boundary in the form of Timms Creek is thought to limit Wairau River influence (Figure 7.11). Piezometric data are useful to understanding groundwater flow directions while oxygen isotope analysis of the waters from these twelve piezometers could help confirm what dominant water type existed at each well. Unfortunately, the extremely small diameter (0.05m) makes inserting a portable submersible pump for sampling difficult and has not yet been carried out. Groundwater flow directions for Timms and Cat Creeks are further discussed in relation to stable isotope results in section 7.5.

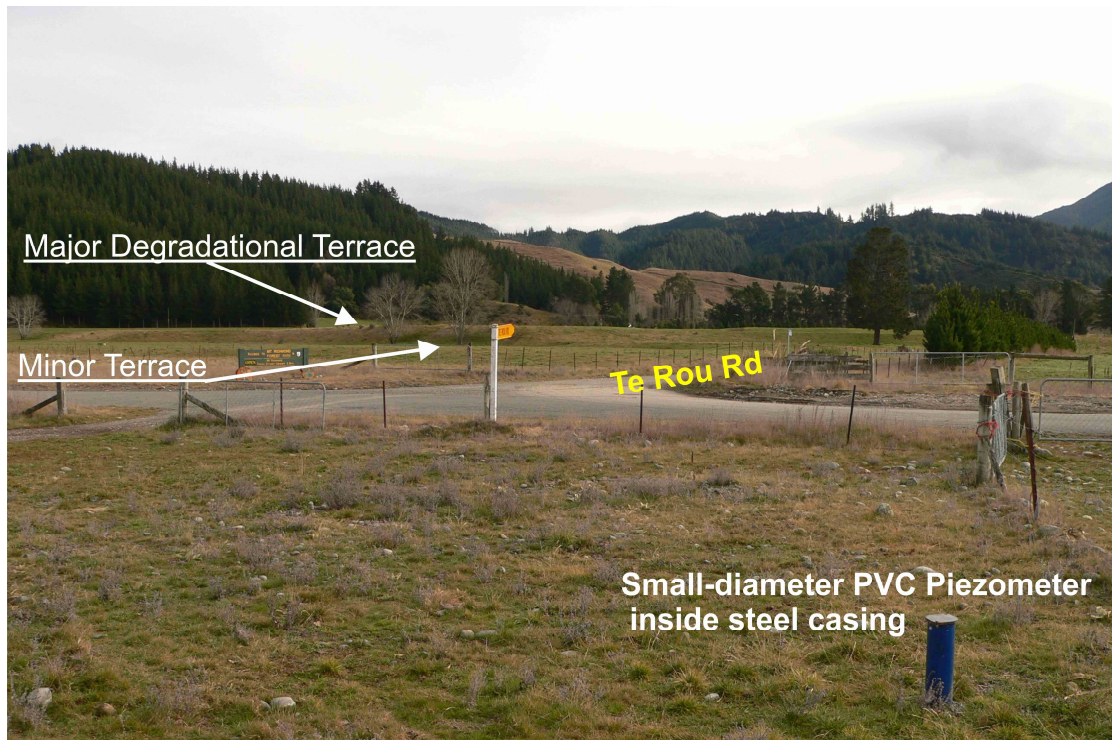


Figure 7.5: Te Rou Rd, looking North-North West. Displayed are a) relatively major Q2 degradational terrace in background b) minor Q2 terrace in middle distance and c) example of small-diameter piezometer in foreground on Q1 Rapaura Formation.

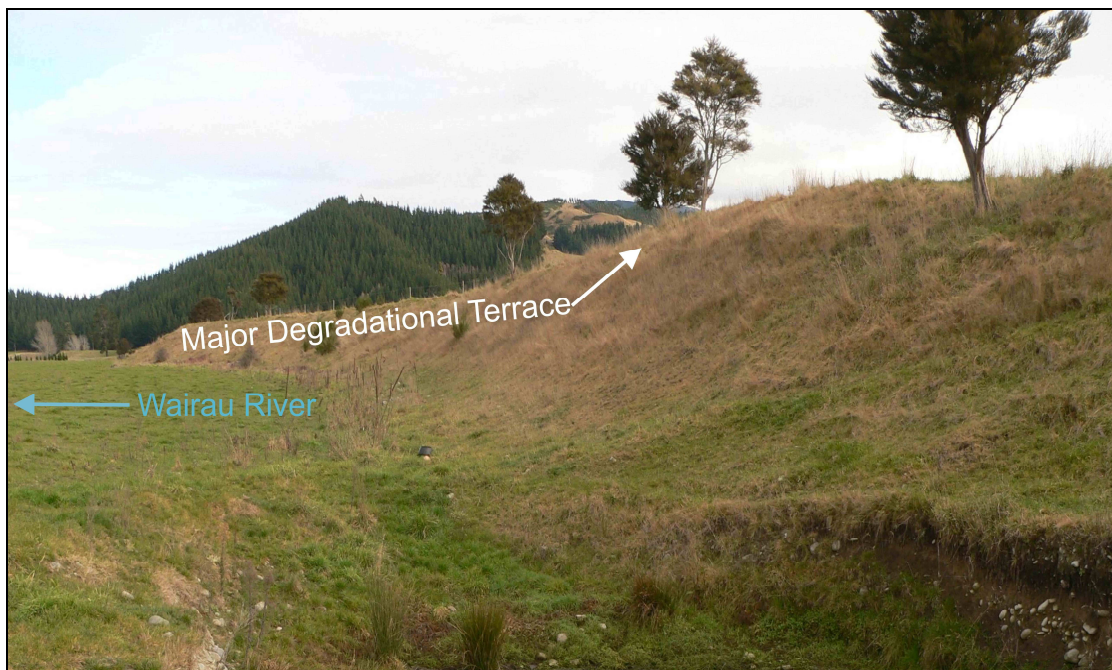


Figure 7.6: Looking west, close up of major Q2 degradational terrace scarp, Timms Creek. The terrace likely forms a geomorphic boundary on Wairau River influence from the south.

No piezometric contours exist for Top Valley in the absence of sufficient wells or piezometers. Similar to the situation in Timms Creek, groundwater flow directions are instead inferred to flow towards a prominent Q2 aggradational terrace (photographed in Figure 7.7). Further east, away from the prominent terrace, the hydraulic boundary of Top Valley Stream likely limits the influence of Wairau River waters. Groundwater flow directions for Top Valley are further discussed in relation to stable isotope results in section 7.5.



Figure 7.7: Above, looking West, view of major and minor terraces that mark Q2 Speargrass Formation gravels, Top Valley. Below, looking North West, view of the same extensive and planar Q2 aggradational terrace with a minor Q2 degradational terrace at its base. Reservoir in foreground situated in low-lying Q1 Rapaura Formation gravels that form the historic Wairau River floodplain.

7.4 HYDROGEOCHEMISTRY

The hydrogeochemistry of Top Valley, Timms Creek and Cat Creek was found to be dilute with generally low dissolved solids. Similar to the Waikakaho catchment, TDS content was found to be higher in groundwater than in surface water, likely due to the longer residence time and greater water-rock interaction. Top Valley Stream yielded TDS values of 40.2 and 39.6 mg/L while the two groundwater sites within Top Valley gave TDS values of 45.4 and 44.8 mg/L. An influence on TDS by the Wairau River from which the two groundwater sites receive recharge (discussed in section 7.5) cannot be ruled out as the TDS content of the nearby Wairau River was 46.2 mg/L, higher than Top Valley Stream, meaning that Wairau River-derived water may elevate Top Valley groundwater TDS levels to approximate its own. Whichever mechanism has resulted in slightly higher TDS levels in Top Valley groundwater (natural groundwater evolution versus Wairau River-influence), the extremely dilute nature of both water sources renders them virtually chemically indistinguishable.

Water chemistry was also unable to differentiate water sourced from North Bank tributaries versus the Wairau River due to both sources sharing a similar chemical signature. Both types plot in the Ca-Na-K-HCO₃ hydrochemical facies (Piper plot, Chapter 4) and produce a calcium-bicarbonate type chemical signature as evidenced by the elongate hexagon-shaped Stiff plots (Figure 7.8). The Stiff plots shown in Figure 7.8 demonstrate that the Wairau river, Top Valley groundwater, Top Valley Stream and Timms Creek all share a common pattern with the only point of difference being the relative size (proportional to TDS content) of each plot. Cat Creek surface water and groundwater likely shares the same pattern, however, no sample was able to be gathered due, in part, to lack of flow in Cat Creek and also the lack of wells.

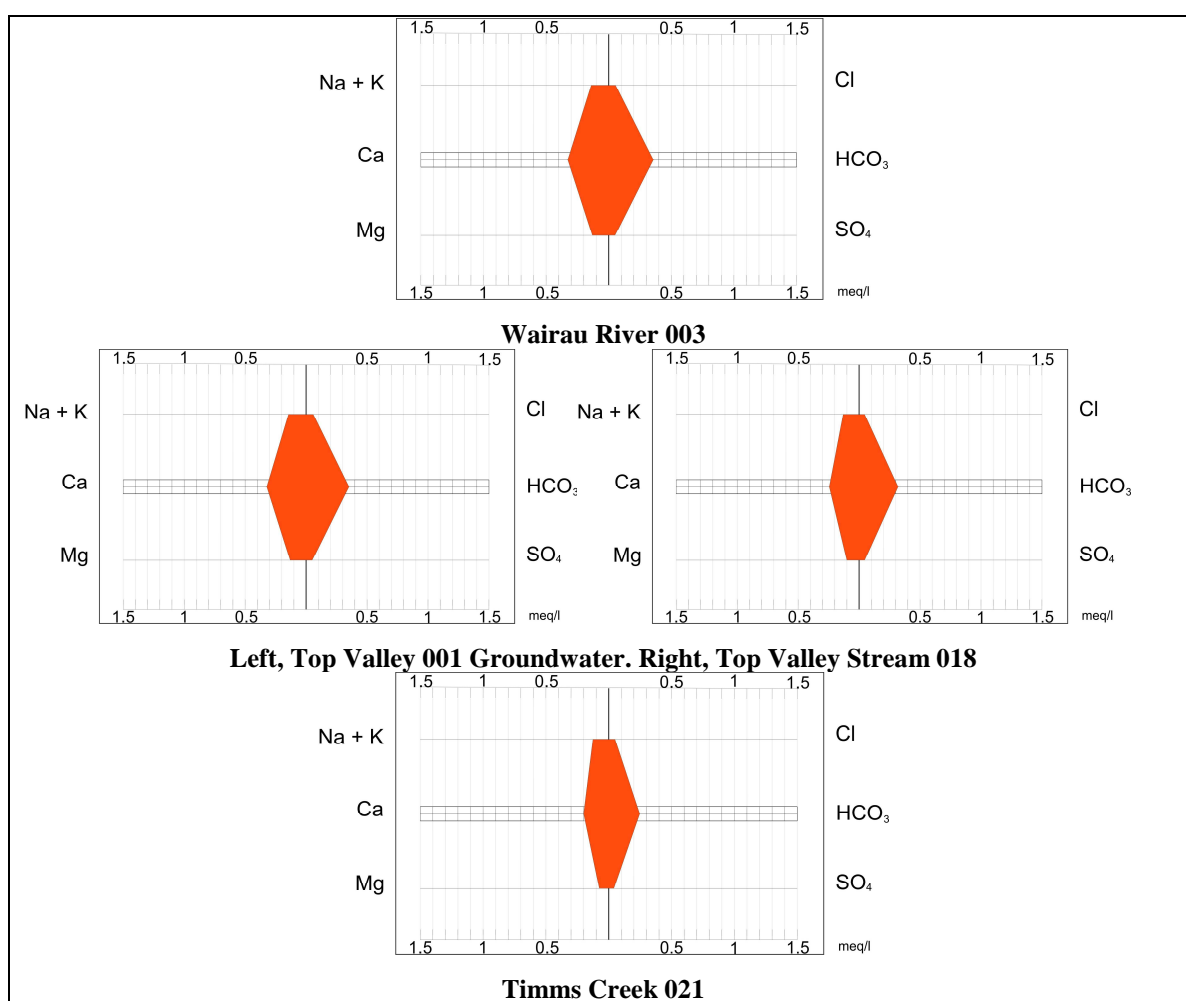


Figure 7.8: Representative Stiff plots from Top Valley and Timms Creek area

7.5 STABLE ISOTOPES

The use of stable oxygen isotopes proved to be a powerful tool in differentiating groundwater that was sourced from the Wairau River versus groundwater that was more local in origin. Figure 7.9 displays the results of the stable isotope survey carried out 3-6 August 2009 with a clear distinction between those waters sourced from the relatively low-altitude Richmond Range and local precipitation (average $\delta^{18}\text{O}$ value circa -7.3‰) and those waters sourced from the Wairau River (average $\delta^{18}\text{O}$ value from this study was -8.51‰).

Based on the distinction in oxygen isotope composition between North Bank-derived water and that derived from the Wairau River, each of the valleys were studied in turn with constraint of the Wairau River-groundwater interface in mind. Figure 7.10 displays oxygen isotope values at the junction of Cat Creek and Wairau River in relation to geology and

geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River with a possible mixing zone thought to exist between the Wairau River given the intermediate oxygen isotope values. No $\delta^{18}\text{O}$ value was collected for the ephemeral Cat Creek as there was no flow at the time of sampling, however, it would be expected to yield a $\delta^{18}\text{O}$ value similar to Timms Creek.

The influence of the Wairau River can be seen to extend reasonably far upon the North Bank with the limit of influence being a terrace scarp which marks the entry onto the Timms Creek floodplain to the north. There, water derived from Timms Creek can be assumed to predominate (and which would be expected to have a $\delta^{18}\text{O}$ value of around -7.26 ‰). South of the terrace scarp, the oxygen isotope signature is quite negative (-7.94 ‰ and -8.26 ‰), signifying the influence of the Wairau River upon groundwater recharge by producing $\delta^{18}\text{O}$ values that fall between that of Timms Creek and the Wairau River (c. -8.5 ‰).

Top Valley, Timms Creek & Cat Creek Oxygen Isotope Results

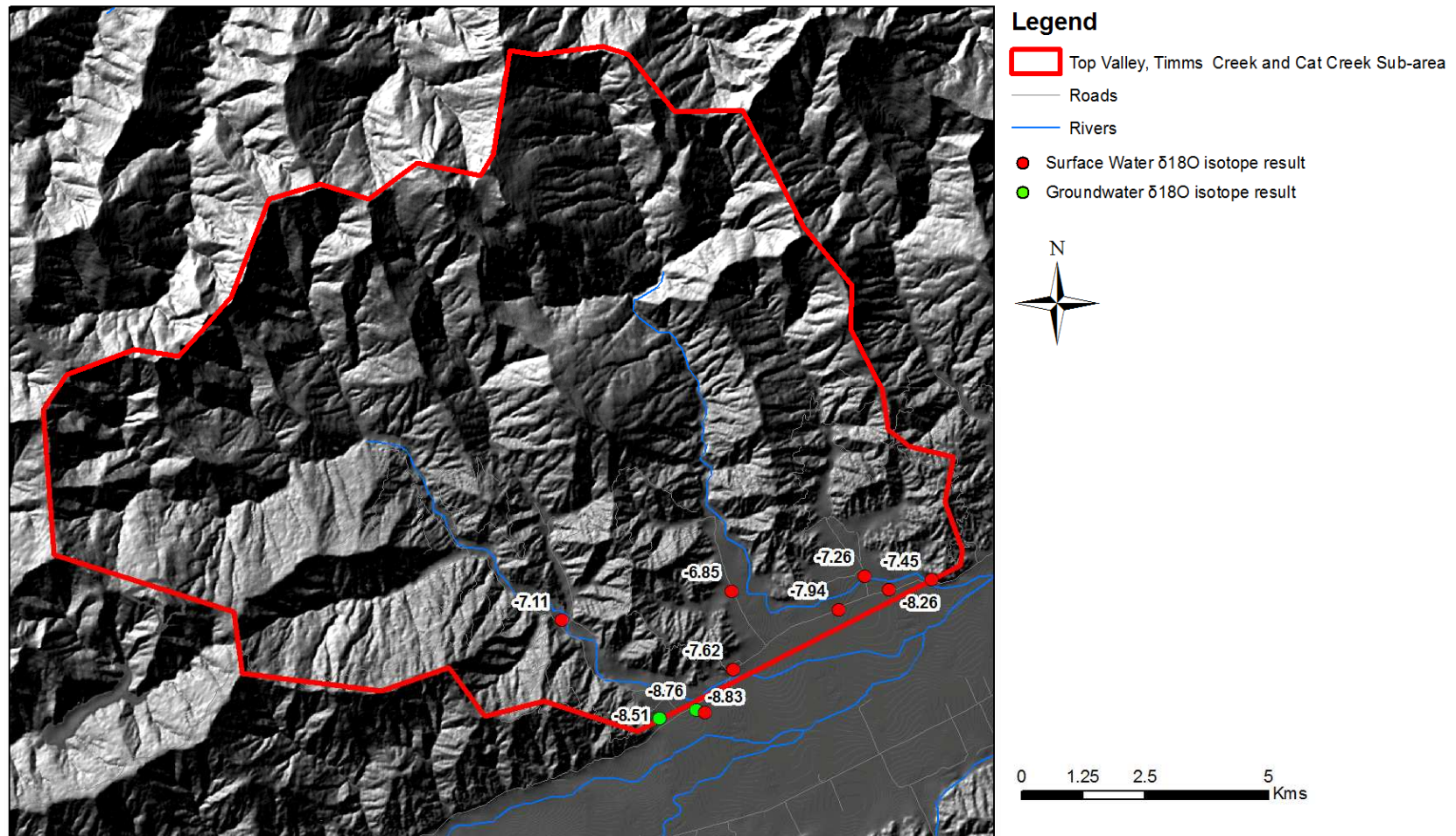
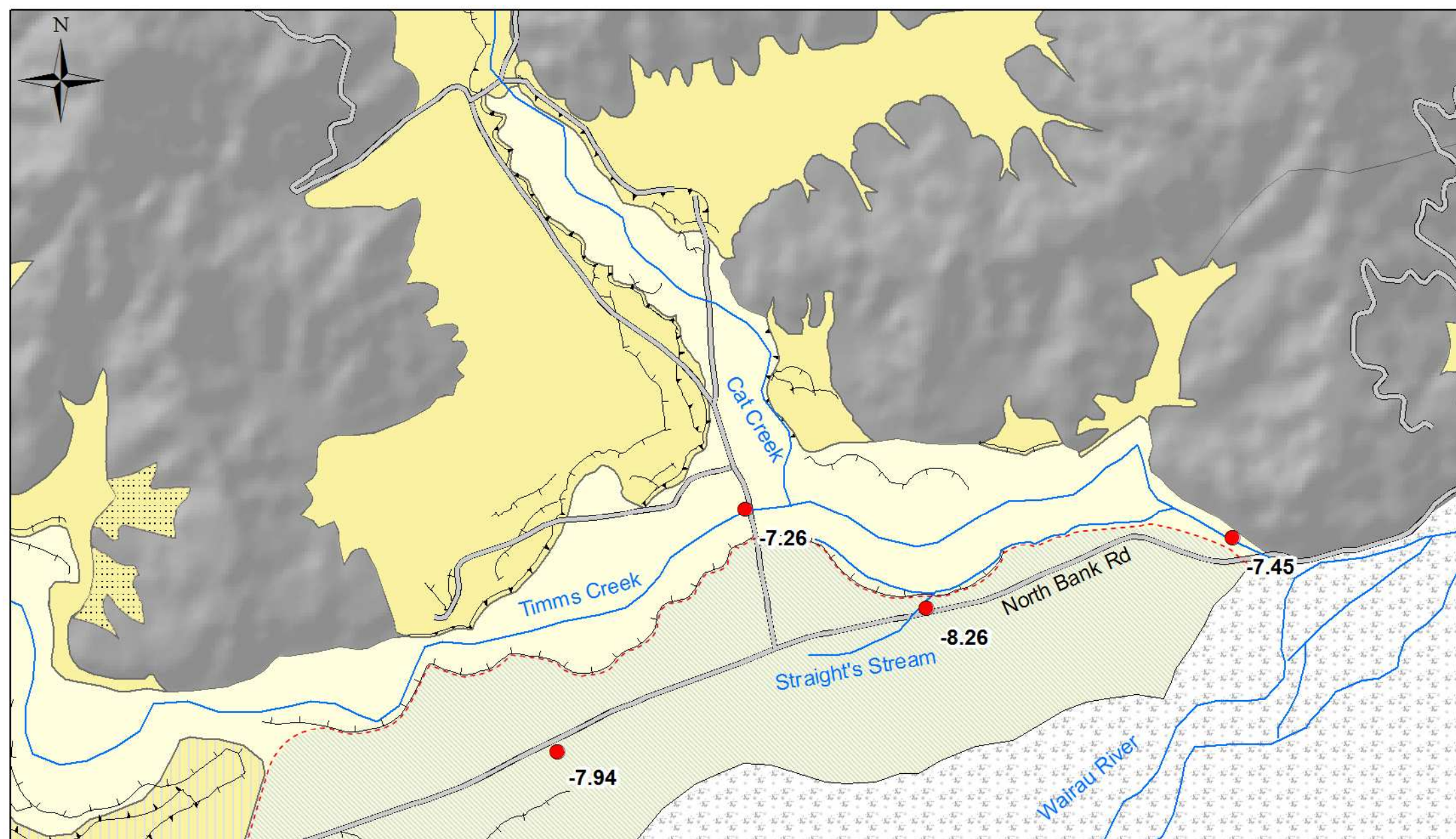


Figure 7.9: Top Valley, Timms Creek and Cat Creek Oxygen Isotope Results from Sampling Survey August 3rd-6th 2009



Legend

- Roads
- Rivers
- Faults

— Terrace Edges (0-2 metres)

— Terrace Edges (2-4 metres)

Q1 Floodplain & Recent Alluvium

Q2 Terrace Cat Creek

Q2 Degradational terrace

Undifferentiated Quaternary Landslide

Greywacke Cat Creek

0 0.25 0.5 1 Kms

● Surface Water $\delta^{18}\text{O}$ isotope result

● Groundwater $\delta^{18}\text{O}$ isotope result

Figure 7.10: Oxygen isotope values at junction of Cat Creek and Wairau River in relation to geology and geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River. The shaded area represents the mixing zone between the red line and the Wairau River.

Further west, Figure 7.11 displays the oxygen isotope value from Burnt Scrub Creek in the Timms Creek area and the interpolation of the Wairau River-groundwater interface in relation to geology and geomorphology. As discussed in section 7.3 when drawing upon piezometric data, the extent of groundwater flow from the Wairau River appears to be constrained geomorphically by a relatively prominent Q2 degradational terrace. This could not be confirmed through the use of stable isotopes by this study in the absence of any wells in the area, other than the network of 12 piezometers. If able to be sampled, groundwater $\delta^{18}\text{O}$ values should approximate an oxygen isotope composition approaching that of the Wairau River. The estimated limit of influence by the Wairau River within the Timms Creek area is instead interpolated from Figure 7.10 to fall at the base of the prominent Q2 terrace scarp in Figure 7.11. This was done not only on a geomorphic basis, but also due to piezometric contours suggesting an influence on groundwater flow directions when the prominent Q2 terrace scarp is intercepted (Figure 7.3). As expected from its geographical position some distance from the Wairau River floodplain, Burnt Scrub Creek gave a $\delta^{18}\text{O}$ value characteristic of the North Bank at -6.85 ‰.

Oxygen isotope values from Top Valley can be seen in Figure 7.12 in relation to geology and geomorphology. Both groundwater sample sites are located on Q1 Rapuara Formation gravels that lie below a prominent aggradational terrace scarp and give $\delta^{18}\text{O}$ values indicative of Wairau River-influence (-8.51 ‰ and -8.76 ‰). With Top Valley Stream giving less negative $\delta^{18}\text{O}$ values of -7.11 ‰ and -7.62 ‰ respectively, the Wairau River can be deemed to be the major source of groundwater recharge within the Q1 Rapuara Formation gravels. As such, the estimated limit of influence by the Wairau River is inferred to coincide with the boundary between Q1 Rapuara Formation and Q2 Speargrass Formation gravels. Further east, the hydraulic boundary of Top Valley Stream likely limits the influence of Wairau River waters with the estimated limit of Wairau-influence bordering Top Valley Stream.

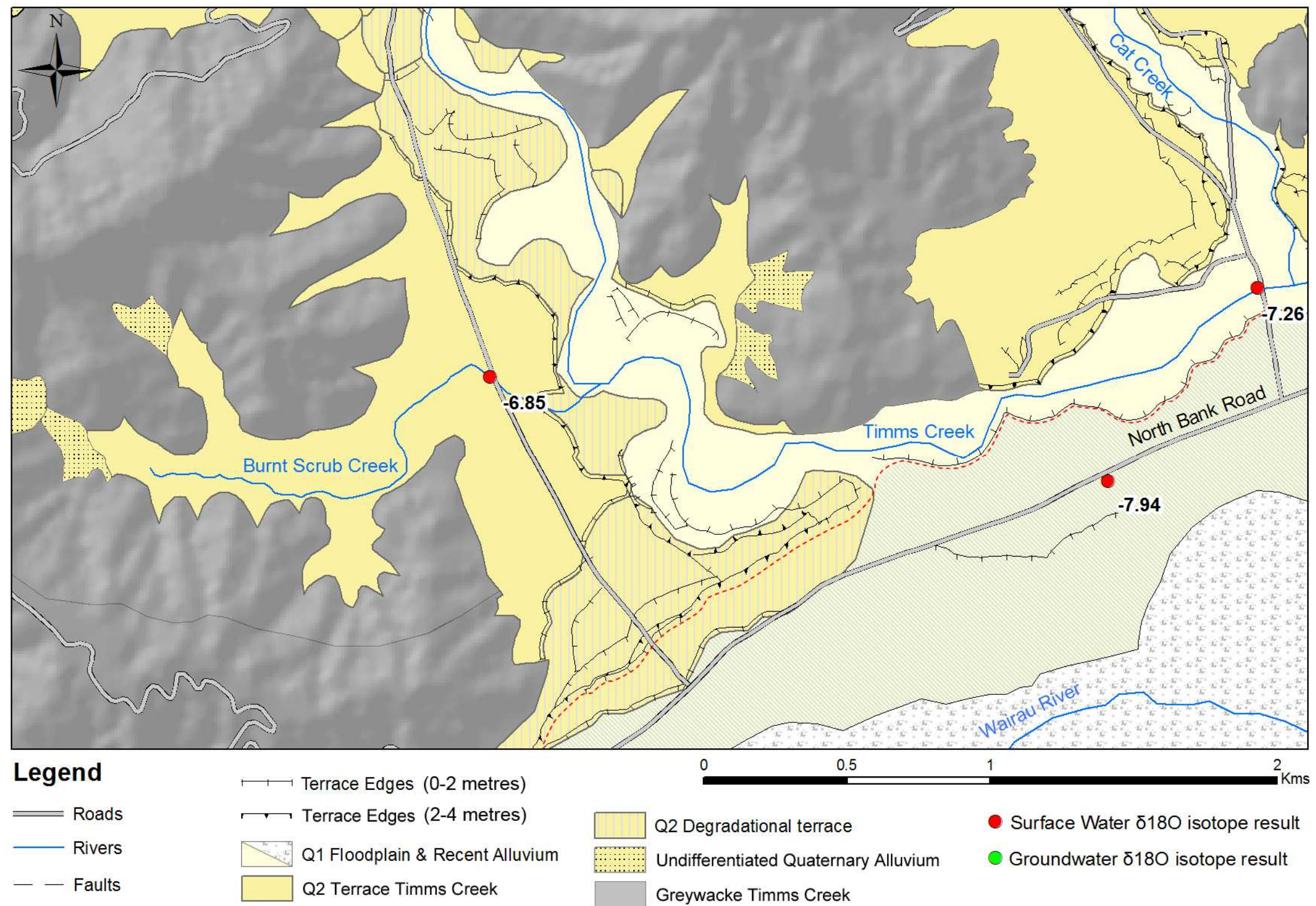


Figure 7.11: Oxygen isotope values at junction of Timms Creek and Wairau River in relation to geology and geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River. The shaded area represents the mixing zone between the red line and the Wairau River

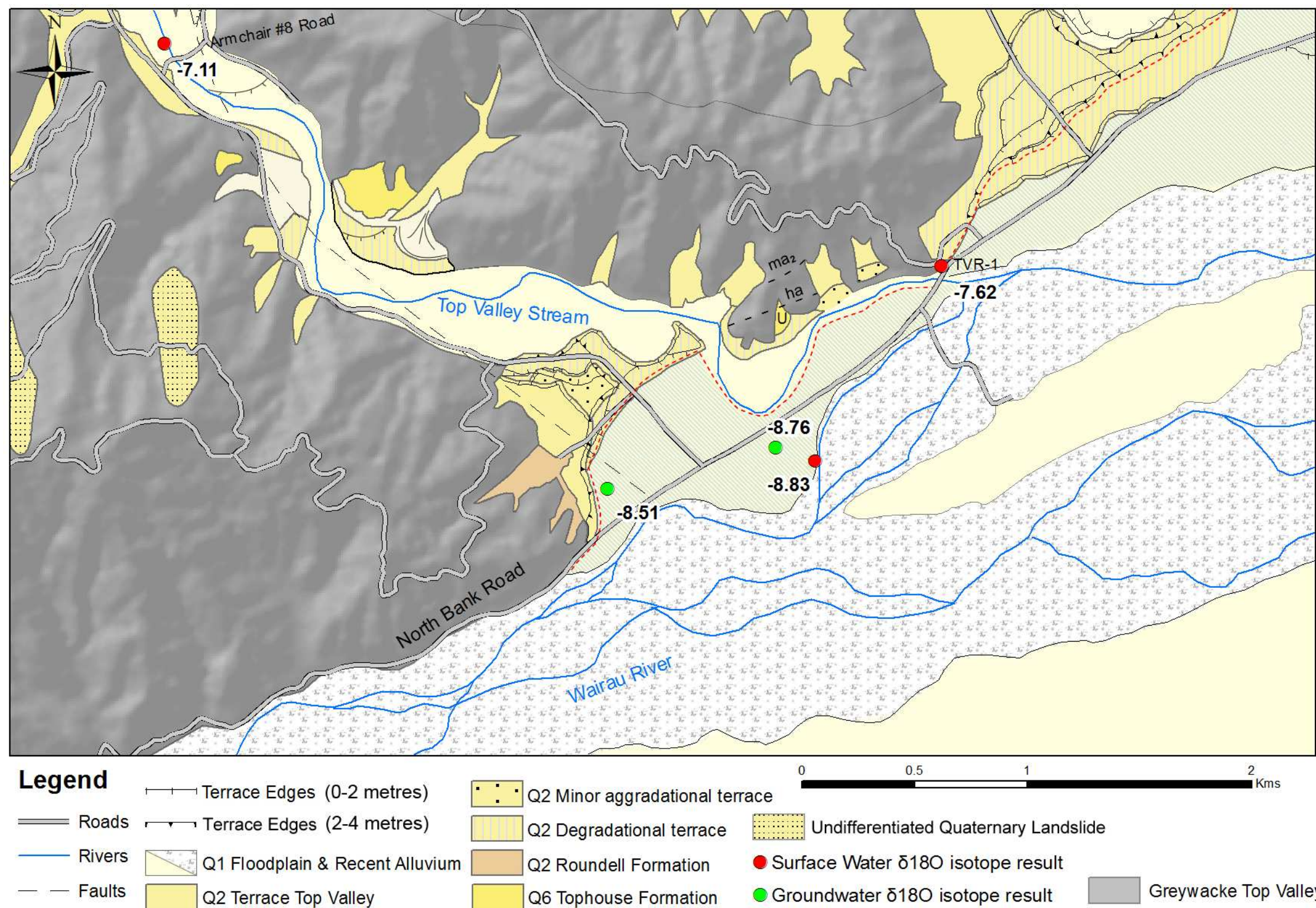


Figure 7.12: Oxygen isotope values at junction of Top Valley and Wairau River in relation to geology and geomorphology. The red line is the estimated extent of influence on groundwater by the Wairau River. The shaded area represents the mixing zone between the red line and the Wairau River

7.6 CHAPTER SUMMARY

Prominent fluvial terraces are present in all three valleys which often separate Q2 Speargrass Formation gravels from Q1 Rapaura Formation gravels. These prominent fluvial terraces impact upon groundwater flow directions through creating geomorphic constraints. In both the Timms Creek and Top Valley areas, relatively prominent Q2 degradational or aggradational terraces limit the influence of the Wairau River upon groundwater. To the east of both prominent terraces in each valley, the North Bank tributaries of Timms Creek and Top Valley Stream respectively form hydraulic boundaries to Wairau River-influence. A piezometric contouring exercise previously carried out in the Timms Creek and Cat Creek area supported a sweeping motion of groundwater flow upon the North Bank in a broad arcuate shape.

The hydrogeochemistry of Top Valley, Timms Creek and Cat Creek was found to be consistent with other North Bank tributary valleys with surface water and groundwater chemically indistinguishable from one another. Groundwater (principally Wairau-derived) tended to have a slightly higher level of TDS than North Bank tributaries, a possible function of longer residence time and further water-rock interaction by groundwater than surface water, or a possible consequence of Wairau River recharge. The hydrogeochemistry of Top Valley, Timms Creek and Cat Creek was also found to be chemically indistinguishable from Wairau River water, likely due to the dilute nature of both types of water.

The use of stable oxygen isotopes proved to be the most powerful tool in differentiating groundwater that was sourced from the Wairau River versus groundwater that was more local in origin. When examined in relation to geology and geomorphology, stable isotopes underlined the importance of the prominent fluvial terraces on limiting the extent of Wairau River-influence.

Chapter 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 THESIS SUMMARY AND CONCLUSIONS

The objectives of this thesis were to define the spatial extent of the North Bank riparian margin, quantify residence time and through-flow in North Bank riparian aquifers and determine seasonal aqueous geochemistry for the North Bank tributary riparian margin. In pursuing these objectives, confirmation and refinement of the current conceptual hydrogeological model for the North Bank riparian margin and tributary valleys has been made with a recommendation for further work. The estimation of the quantity of through-flow of groundwater throughout the North Bank riparian aquifers has not been as successful due to the limited amount and distribution of data for the area.

8.1.2 Geomorphology

Geomorphological mapping of the North Bank found a fluvioglacial dominated topography with a series of fluvial terraces, generally parallel to the Wairau River and tributaries. A prominent 2-4 metre terrace that frequently delineates the Speargrass Formation and Rapaura Formation surfaces is common throughout and is thought to influence groundwater occurrence and flow direction.

8.1.3 Hydrology and Hydrogeology

The North Bank area has a low average low flow specific discharge to the Wairau Rivers, despite the relatively high annual rainfall the area receives. This has been attributed to the influence of North Bank catchment geology where major scree deposits are absent. In mountain catchments, scree plays an important hydrological role by retaining water and slowly releasing it to the rivers. In comparison, the North Bank hydrological response is relatively rapid in the absence of significant scree deposits, and in conjunction with thin soils with limited storage, water is released quickly from North Bank tributary valleys with little water left to contribute in times of low flow.

In the local context, a plentiful groundwater resource exists within the gravels of the Waikakaho Valley, even at a critical time where Waikakaho River levels are low. Drawdown could not be induced in an observation well 17 metres distant from a pumped well during a summer aquifer test, nor a winter aquifer test. No effect on Waikakaho River stage height was observed during aquifer testing further highlighting the abundance of the groundwater resource. Groundwater and river levels were detected to be closely related to one another through water level observations in the Waikakaho Valley lasting nine months, confirming that surface water and groundwater are likely to be a single interconnected resource.

Groundwater flow directions at the junction of a tributary valley and the Wairau Valley were found to be in a broad arc, sweeping onto the North Bank and then returning to the Wairau River. A piezometric contouring exercise previously carried out in the Timms Creek and Cat Creek area supported the movement of groundwater in an arcuate fashion, consistent with the limiting influence of prominent fluvial terraces and the North Bank tributary of Timms Creek to the north. Within each tributary valley, groundwater flow directions are expected to be generally parallel to the main water way.

8.1.4 Hydrogeochemistry

A ground and surface water sampling survey, including subsequent hydrogeochemical data collection, was carried out in August 2009. Both surface water and groundwater upon the North Bank was found to be young, dilute, highly oxidised water, chemically indistinguishable from one another and Wairau River-derived water. A slightly higher concentration of TDS was present within groundwater than surface water which is a reflection of greater residence time and water-rock interaction by groundwater.

Groundwater and surface water upon the North Bank and tributary valleys are predominantly Ca-Na-K-HCO₃ type water from Piper trilinear plot. This corresponds well to previous study on the North Bank with subtle variations present over the study area, such as in the Waikakaho Valley, Bartlett's Creek, and Coatbridge/Langley-dale area. These hydrochemical variations, which produced signatures closer to Na-K-HCO₃-Cl type waters, are likely due to anthropogenic causes such as farming and viticulture. While anthropogenic influence is able to be detected, hydrogeochemistry is unable to differentiate between waters of the Wairau River and the North Bank due to their similar dilute chemical nature.

Seasonal aqueous geochemistry could not be fully examined due to the major ground and surface water sampling survey being carried out only once. However, sites that were sampled twice revealed only minor changes in hydrogeochemistry so that the dilute chemical nature of North Bank waters is expected to be perennially preserved.

8.1.5 Stable Isotopes

Ground and surface waters were sampled for stable isotopes of oxygen and hydrogen as part of a sampling survey carried out in August 2009. Distinct stable oxygen isotope signatures proved useful in delineating ground and surface waters that came from high mountain catchments versus those that arrived more locally at lower altitude.

Constraint of the Wairau River-groundwater interface upon the North Bank was achieved with potential mixing of Wairau River-derived water with North Bank groundwater recognised. Mixing of the two types of water suggests a gradational Wairau River-groundwater interface that can extend over several hundred metres. The importance of geomorphology was confirmed by its limitation of the extent of influence Wairau River to low-lying Q2 Speargrass Formation alluvium, Q1 Rapaura Formation alluvium or the Wairau River channel itself. With groundwater wells relatively scarce upon the North Bank and concentrated close to either the Wairau River or tributary streams, constraint of the Wairau River-groundwater interface is likely to be approximately located and could perhaps shift seasonally. Stable isotopes provide the necessary tool to identify the source of groundwater in all catchments of the North Bank.

8.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Summarised below are the recommendations for future investigations to further define the hydrogeological system of the North Bank and to further constrain the spatial extent of the Wairau River-groundwater interface.

- Conduct a ground and surface water sampling survey, including subsequent hydrogeochemical and stable isotope data collection, during spring, summer or autumn. A sampling survey carried out at a time of year different from this study could observe any seasonal shift in the Wairau River – groundwater interface or change in aqueous geochemistry.

- A longer-term study of precipitation to reveal a possible different and perhaps more dynamic picture of surface/groundwater interactions on the North Bank of the Wairau River.
- Utilise phosphate analyses to confirm fertiliser input to groundwater.
- Conduct a piezometric groundwater survey along the North Bank of the Wairau River. This would enable hydraulic gradients and groundwater flow directions to be established which, in conjunction with hydrogeochemical and stable isotope data collection, would produce a more complete hydrogeological picture.
- Analyse the water chemistry of Timms and Cat Creek utilising the network of piezometers installed there, if possible, to compliment piezometric data. Hydrogeochemical and stable isotope data collection would aid interpretation of groundwater origin and flow direction in this area.
- Observe water levels in neighbouring wells whenever pump testing of a new well takes place. Such water level observation during pumping would constitute an aquifer pump test, at little added cost over a pump test alone. Aquifer test data is scarce upon the North Bank and would confirm hydraulic connectivity as well as allow calculation of hydraulic parameters.
- Continue water level monitoring in the Waikakaho Valley to create a long term record. While Waikakaho River and groundwater levels appear to be intimately related, nine months of water level data are insufficient to determine what seasonal trends exist between Waikakaho River stage height and groundwater levels.

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